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EXPERIMENTAL INVESTIGATION ON CYCLIC BEHAVIOR OF STEEL SHEAR WALLS

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ABSTRACT

In the past three decades, steel shear walls have been used in numerous tall buildings as a resistant system against earthquakes and wind loads. The advantages of using these systems in seismic resistant structures include enhanced stiffness, strength and ductility. In addition, more stable hysteresis characteristics are resulted which leads to considerable capacity for absorption of plastic energy. In the present paper, the elasto-plastic behavior of steel shear walls is presented by performing cyclic tests on six different specimens. The aspect ratio of shear walls and also the thickness of infilled panels are considered as variables and their effects on the cyclic behavior are studied thoroughly. Finally, the experimental results are compared with theoretical analysis and a good agreement is observed.

Keywords: steel shear wall, hysteresis loop, tension field, cyclic behavior

1. INTRODUCTION

The post-buckling strength capacity of thin steel plates caused steel shear walls to be realized as a desirable system against lateral loads all over the world, particularly in Canada and USA. Different static and quasi-static tests were performed on steel shear walls since 1983, and the elasto-plastic behavior of steel shear plates was studied from pre-buckling to post-buckling stages. The tests conducted by Timler and Kulak [1] on a two-story unstiffened steel shear wall in Alberta University, showed good agreement with analytical results obtained by Thurburn [2]. Driver et al [3] reported the results of cyclic tests on a four story unstiffened steel shear wall.

Based on the above experiments, Lubell and Rezaii [4] performed tests on two specimens of one story steel shear wall. Sabouri-Ghomi and Roberts [5] reported sixteen diagonal tests on steel shear walls. Elgaali and Caccese [6] performed analytical and experimental tests on three-story shear walls. Also Astaneh-Asl and Zhao [7] reported their tests on steel shear walls in the University of Berkeley.

In the present paper, the elasto-plastic behavior of steel shear walls is presented by

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performing cyclic tests on six different specimens. The aspect ratio of shear walls and also the thickness of infilled panels are considered as variables and their effects on the cyclic behavior are studied thoroughly. Finally, the experimental results are compared with theoretical analysis and a good agreement is observed.

2. DESCRIPTION OF THE TESTS

2.1 General points

Six specimens of steel shear walls were made in the workshop of *Pol-Soleh Company*, to study their cyclic behavior. Then the samples went through cyclic loading in structural laboratory of Building and Housing Research Centre. The specimens are shown in Figs. 1,2 and 3. In order to assess different features of the steel shear walls, the specimens were made in various aspect ratios and also panel thicknesses.

2.2 Details of fabrication

As illustrated in the Figs. 1,2 and 3, the internal dimensions of plates for wide , square and long specimens are 1420×920, 920×920 and 920×1420 (all in millimeters), respectively.

The boundary members are 2UNP140 with strengthening plate of 80×8 (mm^2) added to their webs using pinned joint at beam-column connections. Then a steel panel is fixed on the boundary members by frictional bolts of A490 on both sides. In addition, the corner bolts were left unfastened to insure proper hinge performance.

All specimens were fixed on a strong floor using plates of 2700×200×30 and 2100×200×30, (all dimensions in millimeters) and welded by two straight fillet, each with size of 8mm. Also, two steel brackets were included in each side of the upper beams for application of cyclic lateral loads.

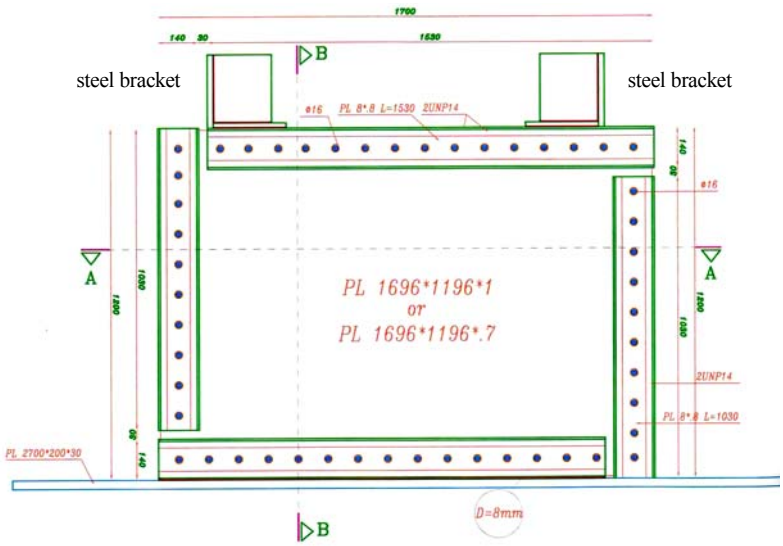

Figure 1. Geometric characteristics of two wide steel shear walls with thickness of 0.7 and 1mm

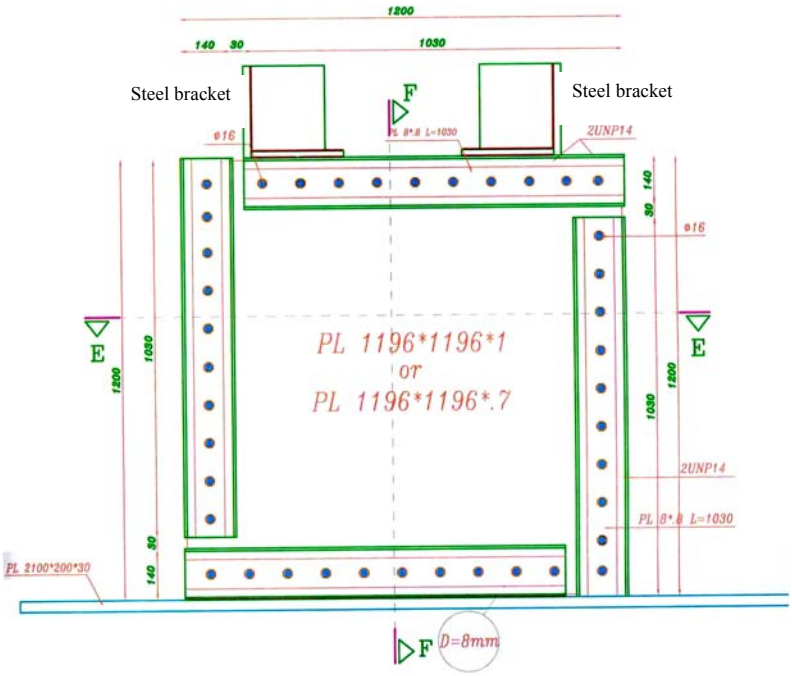

Figure 2. Geometric characteristics of two square steel shear walls with thickness of 0.7, 1mm

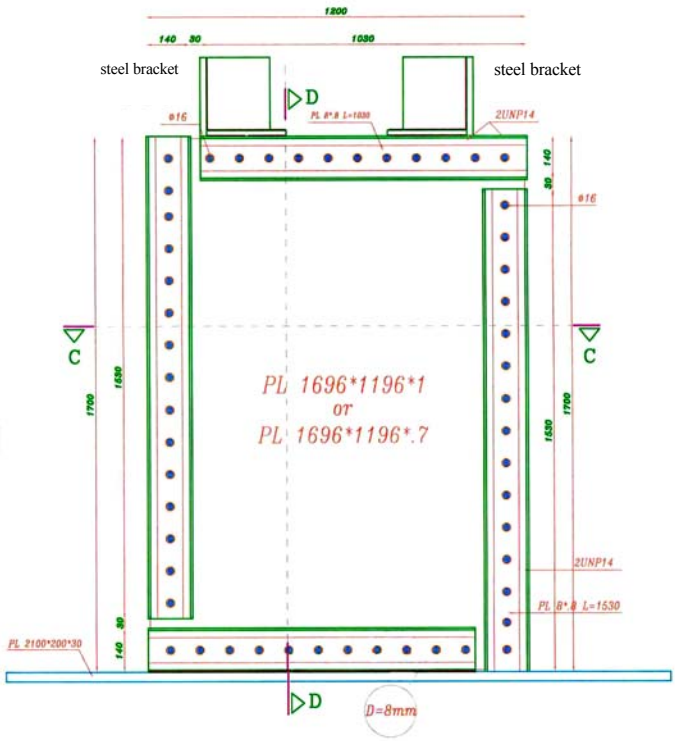

Figure 3. Geometric characteristics of two long steel shear walls with thickness of 0.7, 1mm

2.3 Steel plate characteristics

Steel plates used in the specimens have thicknesses of 0.7 (mm) and 1 (mm). The behavior of these specimens under standard tensile tests is illustrated in Fig. 4 together with characteristics as follows:

$$F_y = \begin{cases} 26.63 \text{ MPa} & t=0.7 \text{ mm} \\ 22.83 \text{ MPa} & t=1.0 \text{ mm} \end{cases}$$

$E=20$ GPa

$G=8.08$ GPa

$E_t=63.0$ kPa

$F_u=33$ kPa

$\nu=0.3$

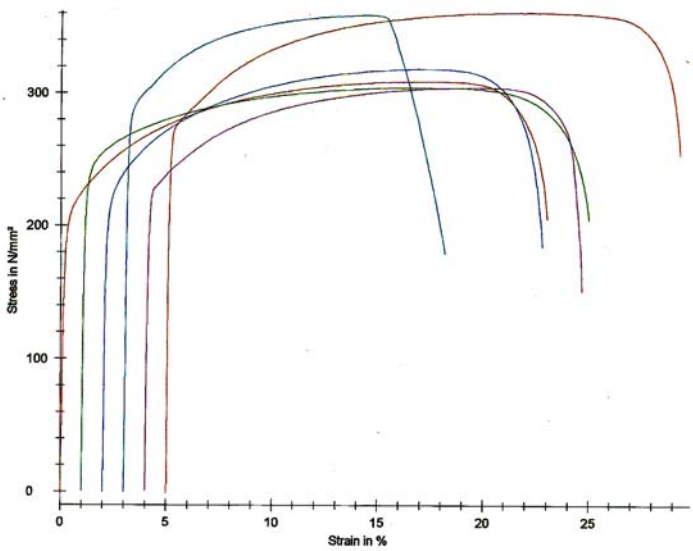

Figure 4. Stress-strain curve of the shear panel

2.4 Test results

The required tests were performed by applying lateral loads through the steel brackets connected to the top beam. Initially the load was applied to achieve a given displacement and then the specimen was unloaded. Subsequently the load direction was reversed to reach to opposite of the initial displacement, and then one cycle of loading process was completed. This process was repeated as long as the required numbers of the cycles were acquired.

2.4.1 Wide rectangle with thickness of 0.7(mm)

The calculated initial yielding displacement for the specimen explained above was δ_y=2.1 (mm). Hence the cyclic tests were performed up to this lateral displacement and also on its

multiples. The specimen could undergo one elastic cycle and nine inelastic cycles during the test procedures. Since the variation in the resulted loading became unnecessarily slow, the drift intervals were extended after $5\delta_y$ to reduce the test time. Under this loading condition, the specimen underwent 17 inelastic cycles until the first appearance of cracks in the weld at the bottom beam. The hysteresis loops of above mentioned cyclic loading are depicted in Fig. 5.

2.4.2 Wide rectangle with thickness of 1(mm)

In this specimen, the calculated displacement was also δ_y=2.1 (mm). Hence the cyclic loading was similar to the procedures described in section 2.4.1. The specimen then underwent one elastic and 11 inelastic cycles. As mentioned earlier, it went through 25 inelastic cycles before completion of cycles.

Figure 6 shows the hysteresis loops for the specimen mentioned in this section.

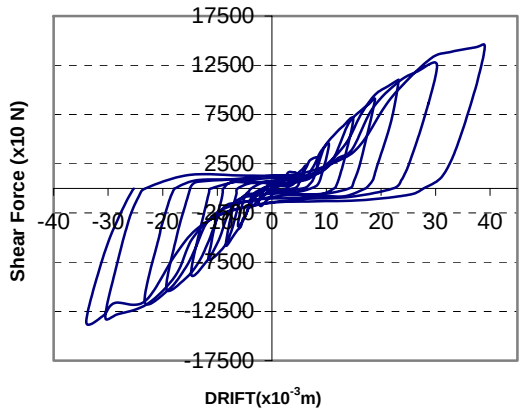

Figure 5. Hysteresis loops of the wide specimen (0.7mm)

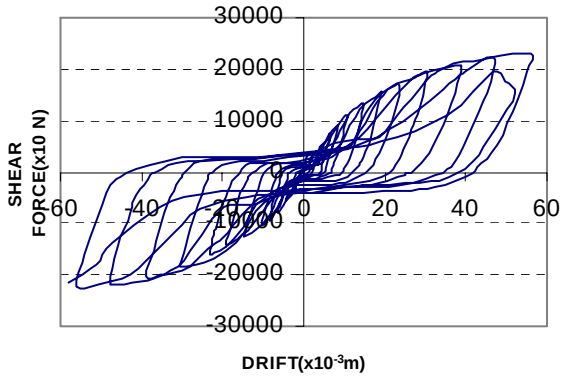

Figure 6. Hysteresis loops of wide specimen (1mm)

2.4.3 Square with thickness of 0.7(mm)

In a similar manner, the hysteresis loops for the square panel of *0.7(mm)* thick was obtained and the results is shown in Fig. 7. The drift at the initial yielding was also δ_y=2.1 (mm). The loading procedure was the same as the ones described in 2.4.1 and 2.4.2 with one elastic and eleven inelastic cycles. Then drift intervals were extended so that the number of cycles was increased to 25, in order to speed up the test.

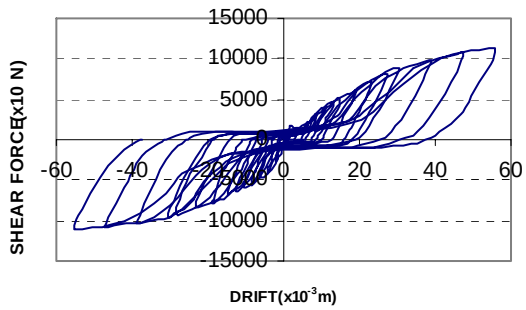

Figure 7. Hysteresis loops of square specimen (0.7mm)

2.4.4 Square with thickness of 1(mm)

For square specimen with thickness of *1(mm)*, using the same loading history, the results are shown in Fig. 8. The number of cycles was one elastic and eleven inelastic which extended to 25 as explained earlier.

2.4.5 Long rectangle with thickness of 0.7(mm)

On this long specimen, the drift was taken as δ_y*=3.2(mm)*. The cyclic tests were performed for this amount of lateral displacement and its multiples which resulted in one elastic and twelve inelastic cycles. Finally the drift intervals were extended, along with the increase in the number of inelastic cycles to 26. The resulted loops are shown in Fig. 9.

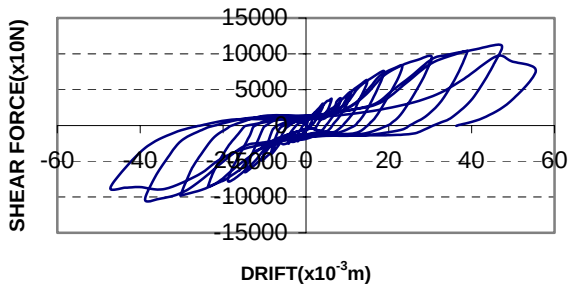

Figure 8. Hysteresis loops of square specimen (1mm)

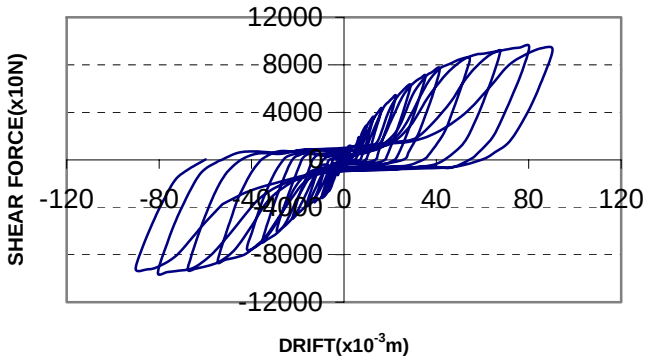

Figure 9. Hysteresis loops of long specimen (0.7mm)

2.4.6 Long rectangle with thickness of 1(mm)

For this specimen, using similar conditions as in section 2.4.5 and drift values of δ_y*=3.2 mm*, the hysteresis loops are illustrated in Fig. 10. The specimen went through one elastic and eleven inelastic cycles and extra 24 cycles with extended intervals, as before.

2.5 Effects of geometrical variations

Comparing hysteresis loops of specimens with common aspect ratios and various thickness reveals that increased thickness would enhance shear strength of the specimens and reduce the drifts. For example, in wide rectangle specimen with thicknesses of *0.7 mm* and *1 mm*, the shear strength were *145 kN* and *231kN*, repectively. Also the corresponding drifts were *38.7 mm* and *16.8 mm*. In addition by increasing the height of specimens, the shear strength reduces while the drift increases. For instance, for square and long specimens with thickness of *0.7 mm*, the shear strength were *112 kN* and *85 kN* , respectively. The drifts are also *34 mm* and *85 mm*, respectively.

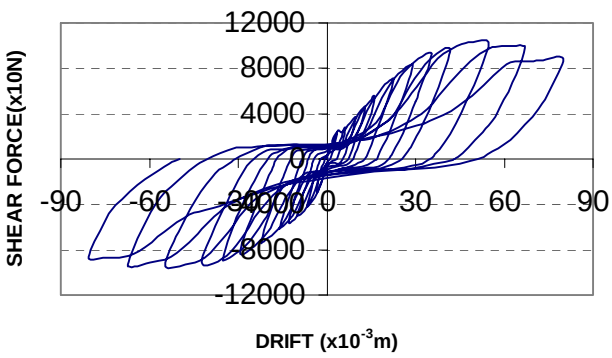

Figure 10. Hysteresis loops of long specimen (1mm)

In a similar manner, for specimens with the same heights and thickness, wider panels result in larger shear strength while the drift values would not change considerably. For instance, in the square and wide specimen, the shear strength were *112kN* and *231kN*, respectively while the drifts in the similar loads were almost the same.

3. EVALUATION OF PLASTIC ENERGY ABSORPTION

As discussed earlier, plastic energy absorption is one of the key advantages of steel plate shear walls as a resisting system against lateral loads. This absorbed energy can be represented with the area surrounded by the hysteresis loops. From Figs. 14.a-f, the absorbed energy was found as 5746, 17511, 8218, 7911, 12004, 11510 (Joule). The achieved ductility of test specimens in the relative drifts of 38.7/920, 55.5/920, 85/1420 during cyclic loading tests was near the 5%. Hence considerable amounts of energy were absorbed in different samples.

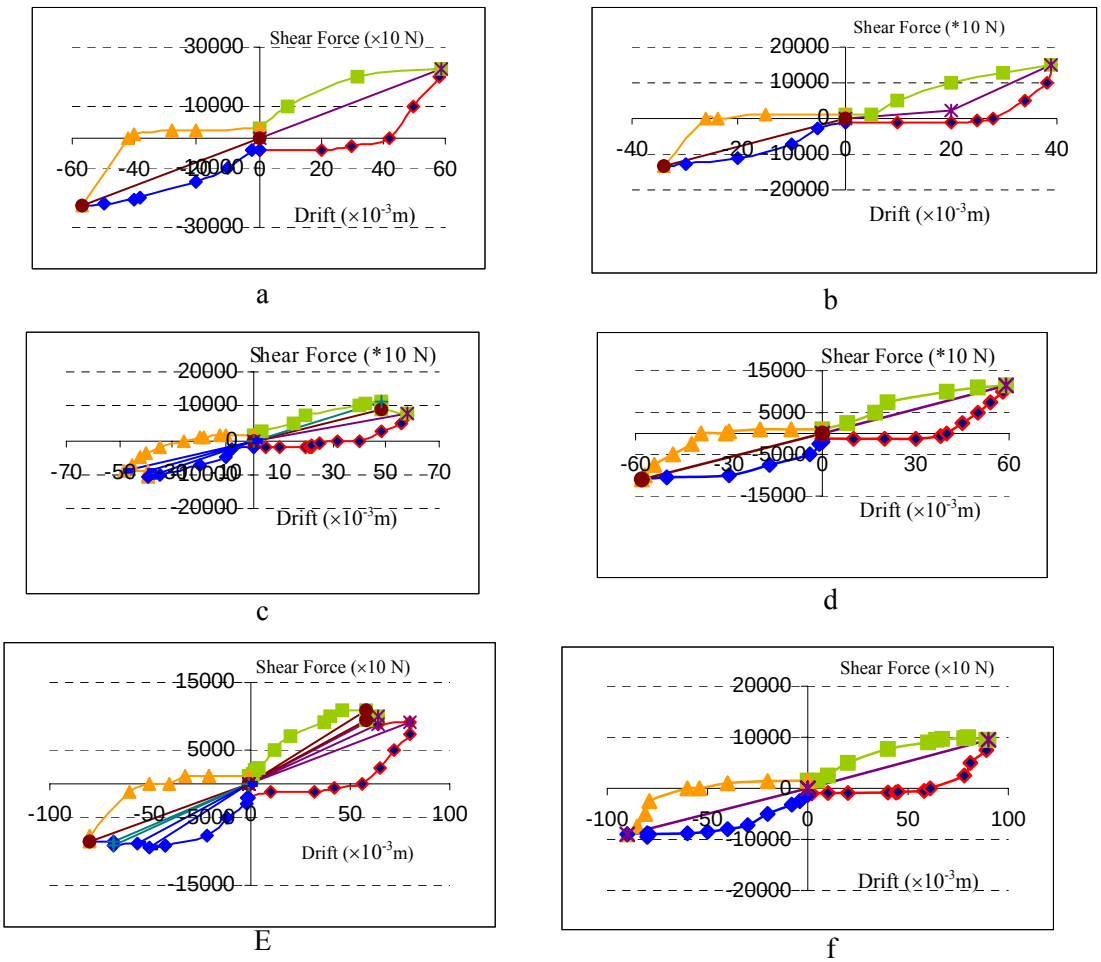

Figure 11. Energy absorption of specimens

4. STUDY OF THEORETIC BEHAVIOR

The behavior of infilled shear panel of steel shear wall can be verified in three regions as follows:

1. Pre-buckling behavior
2. The elasto-plastic behavior after buckling until the yield of the plate.
3. Plastic behavior beyond the yield up to failure

4.1 Prebuckling behavior

In this region, the lateral load is increased until the buckling of plate. The classical relationships of the plates can then be established and the resulted critical shear stress in this region is written as:

$$\tau_{cr} = \frac{k\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{b}\right)^2 \tag{1}$$

where E is the elastic module of shear plate, ν is poison's ratio, t is the thickness and b, d are the width and height of the plate, respectively. Also k is

$$k = 5.35 + 4\left(\frac{b}{d}\right)^2 \qquad \frac{b}{d} \geq 1$$

$$k = 5.35\left(\frac{b}{d}\right)^2 + 4 \qquad \frac{b}{d} \leq 1$$

So the lateral load in this region is:

$$F_{cr} = b\ t\ \tau_{cr} \tag{2}$$

Also for lateral displacement, we have:

$$U_{cr} = \frac{\tau_{cr}}{G} d \tag{3}$$

in which G is shear modules of steel plate. Figure 11 shows the above mentioned parameters.

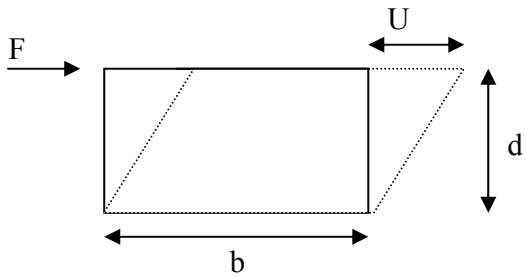

Figure12. Parameters used in pre-buckling equations

4.2 Elasto-plastic behavior of the plate

Generally pre-buckling strength of the full-scale panels is usually neglected, as geometrical imperfections can not be avoided in practice. In the present research these pre-buckling effects are crucial part of analysis, since the steel plate has been gently pre-tensioned during the fabrication process and hence the imperfection was minimized. The post-buckled elasto-plastic behavior of the plate is initiated by forming the tension field, and continues until the principle tensile stress reaches to the yield stress on the entire panel.

The web plate can be replaced by diagonal tensile strips with angle θ as shown in Fig. 12.

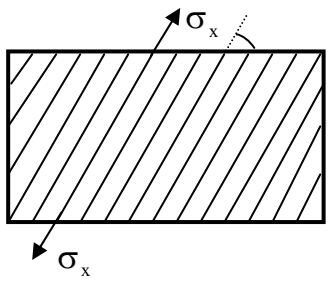

Figure 13. Diagonal strip model of a shear panel

The value of θ is given by CAN/CSA- 316.1-94 as follows:

$$\theta = \tan^{-1}\left[\frac{1+\dfrac{tb}{2A_c}}{1+td\left(\dfrac{1}{A_b}+\dfrac{d^3}{360I_c b}\right)}\right]^{\frac{1}{4}} \tag{4}$$

where A_c and I_c are the cross section and moment of inertia of boundary column, respectively. Also A_b is the cross section of boundary beams. With these assumptions we have:

$$F_e = (\tau_{cr} + 0.5\sigma_e \sin 2\theta)bt \tag{5}$$

where σ_e is the yield stress of the plate and can be written using Von-Mises criteria as follows.

$$\sigma_e = F_y - \sqrt{3}\,\tau_{cr} \tag{6}$$

and

$$U_e = \left(\frac{\tau_{cr}}{G} + (1+\nu')(\frac{\beta\sigma_e}{E})\right)d \tag{7}$$

in which $\nu' = 0.5$ is the plastic poison's ratio and β is a coefficient defined as follows:

$$\beta = \frac{2+\alpha}{3} \tag{8}$$

α is the strain distribution coefficient and varies between 5 in thick plates with flexible boundary members to 20 in thin plates with rigid boundary members. Hence we have:

$$2.32 \le \beta \le 7.33 \tag{9}$$

5. COMPARISON OF EXPERIMENTAL AND THEORETIC RESULTS

For wide rectangular plate with thickness of 0.7(mm), assuming b=1420(mm), h=920(mm), t=0.7(mm) and F_y=266 (MPa) and using equation (1), we can obtain:

$$\tau_{cr} = 0.66 \text{ MPa}$$

From equation (6), we can find:

$$\sigma_e = 265 \text{ MPa}$$

Considering equation (5), we can calculate

$$F_e = 132360 \text{ N}$$

Then by using equation (7) we will have

$$U_e = 1.75 \times 10^{-2} \text{m}$$

The test results are in good agreement with theory with accuracy of less than 0.1 mm, as shown in Fig. 13-a.

For wide rectangular plate of the second type, by repeating the previous calculations with t=1(mm) and F_y=228 (MPa), similar agreement between test and theoretic results are achieved with 0.1mm accuracy as shown in Fig. 13-b.

Also for the square plate with the thickness of 0.7 (mm), replacing h=b=0.92(mm), t=0.7(mm), F_y=266(MPa), a deviation of 2.5(mm) were obtained between the theoretical and test results as shown in Fig. 13-c.

For the second square plate, replacing t=1(mm), F_y=228(MPa) in the previous section, leads to a good agreement with 0.1(mm) accuracy as shown in Fig. 13-d.

For long panel with thickness of 0.7(mm), replacing b=920(mm), h=1420(mm), t=0.7(mm), F_y=266(MPa), the same agreement between theoretical and experimental results are obtained as shown in Fig. 13-e.

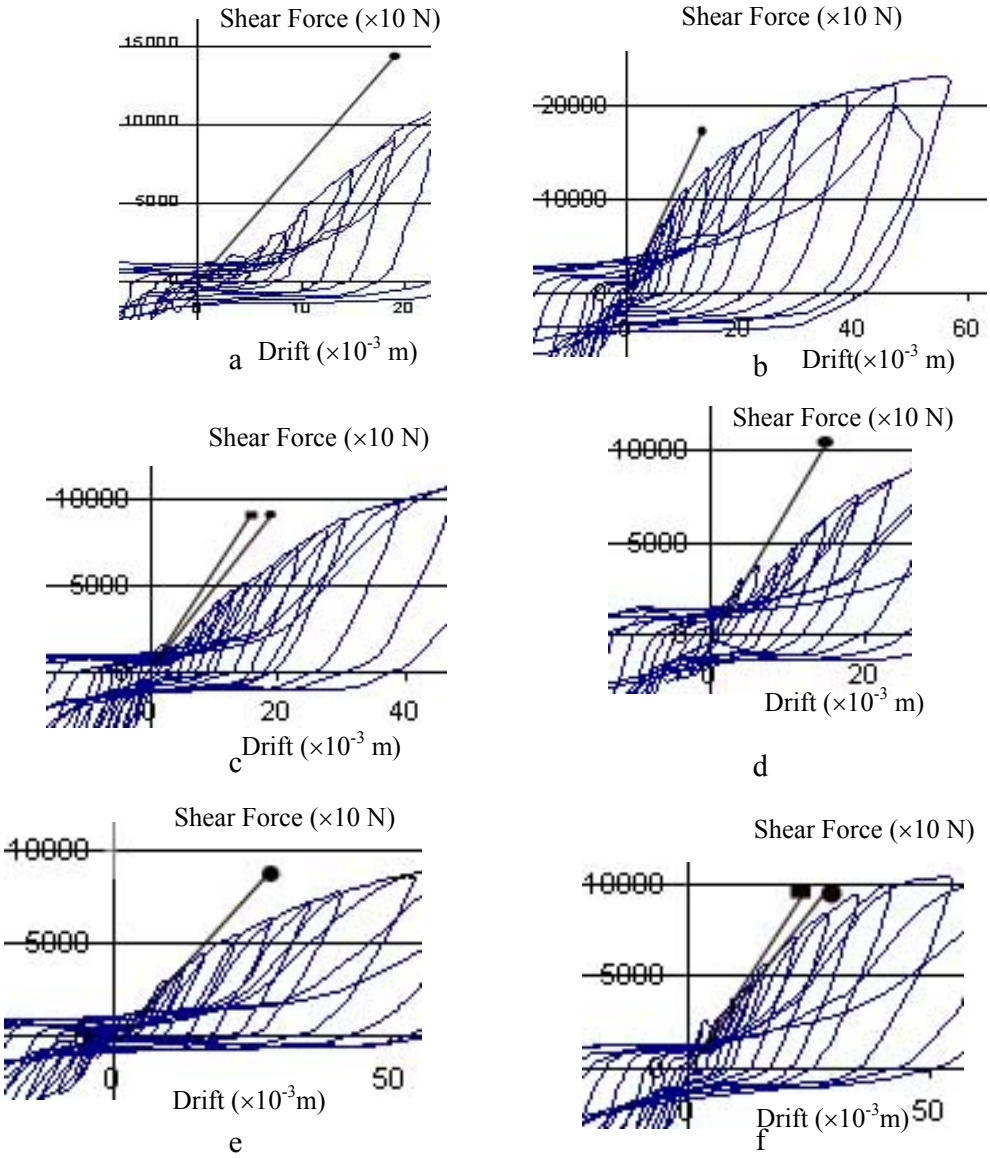

Figure 14. Comparison of experimental and theoretical results

Finally for the second long panel, replacing t=1(mm), F_y=228 (MPa) the corresponding error between theoretical and experimental results is 1.9mm as shown in Fig. 13-e.

6. CONCLUSIONS

Significant amounts of ductility are achieved for the test sepcimens with considerable energy absorption. Reduction of the height in the shear panels results in decreasing of drift

and enhancement of shear strength. On the other hand, increasing the height of the panels improves panel drift and causes significant plastic energy absorption which leads to smaller reduction on the shear strength. Using a wider panel presents significant increase on their shear strength and reduction of drifts. Experimental and theoretical results are generally in a good agreement.

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