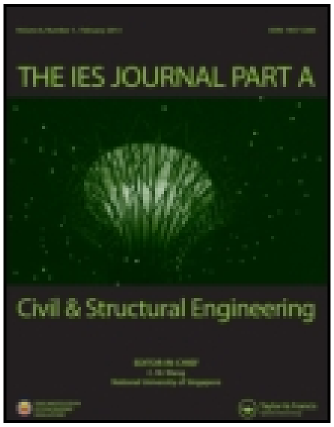

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Effects of using low yield point steel in steel plate shear walls

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TECHNICAL PAPER

Effects of using low yield point steel in steel plate shear walls

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Steel plate shear walls are lateral load resisting systems, especially against earthquake excitation. They are constructed with or without stiffeners. Stiffened walls are more ductile than those without stiffeners. In this research a numerical study using finite element analysis via a finite element program is conducted. Nine thin steel plate shear wall models were considered in three groups of 5-storey, 10-storey and 15-storey walls. In each group different yield point steel for the infill plate was used. The yield points of infill plates were assumed to be 160, 200 and 240 MPa. The results showed that using low yield point (LYP) steel will increase energy dissipation of models by up to 63%. Using LYP steel also decreases the lateral displacement of models by up to 16%.

Keywords: steel plate shear wall; low yield point steel; energy dissipation; shear capacity

1. Introduction

In the current seismic-resistant design, building structures are allowed to exceed their elastic limit under severe earthquake excitation. However, brittle collapse of a building should be prevented. Besides strength requirements, stiffness is another concern in a structural design. With high strength and high stiffness, the steel plate shear wall (SPSW) has drawn many engineers' attention. Research works have been carried out on the SPSWs. Experimental studies have been carried out on the thin SPSWs by Caccese, Elgaaly, and Chen (1991), Driver et al. (1997) and Lubell et al. (2000). Analytical studies on the shear buckling behaviour of steel plate wall and the behaviour of a multi-storey steel wall system were conducted by Elgaaly, Cassse, and Du (1993), Elgaaly and Caccse (1995), Driver et al. (1997), Berman and Bruneau (2003) and Sabouri-Ghomi, Ventura, and Kharrazi (2005). Design rules of the thin SPSW are also specified in the design specifications, such as AISC (2005a) and CSA (2009).

SPSW systems have been applied in building construction. The steel plate used in the shear wall is usually very small in thickness due to the high-strength steel used. The elastic shear buckling of the thin plate steel shear wall usually results in reduced strength, stiffness and energy dissipation capacity. Although the tension field action (TFA) is able to provide the post-buckling strength, however, if the shear buckling occurred in the early stage, out-of-plane permanent deformation may affect the serviceability of the thin plate shear wall under small or moderate earthquake excitation. To defer the shear buckling and increase the energy dissipation capacity, stiffening devices can be used for the plate wall. These can be done by adding steel stiffeners, which is quite common in Japan. A composite shear wall that adopts reinforced concrete to restrain the steel plate wall was also reported with good seismic resistance by Zhao and Astaneh-Asl (2004).

A new type of structural steel, low yield point steel (LYP steel), has been developed and applied in seismic-resistant design (Saeki et al. 1998). The LYP steel possesses extremely low yield strength and high elongation capacity. The yielding stress of this type steel can be as low as 160 MPa (DIN ST 12 steel), which is about two-third of the conventional structural steel such as DIN ST 37 steel. In this study, ST 12 steel was selected for the plate wall and ST 37 steel was used for the boundary frame. It is shown that the LYP steel has a superior elongation capacity. The LYP steel also possesses low yield ratio, the ratio between the yield stress and the ultimate stress (Fy/Fu), which is 0.64. With low yield ratio, the structure that utilises LYP steel is able to redistribute the inelastic stress easily and provides a larger plastic zone. Due to its superior deformation capacity, LYP steel was also used in the steel dampers to dissipate earthquake energy as reported by Saeki et al. (1998), Chen and Kuo (2004) and Kondo et al. (2001). LYP steel can be used in the steel shear wall as well. The hysteresis behaviour of LYP steel plate has been examined and a two-force strip model was proposed to predict its in-plane strength by Chen and Jhang (2006). In this reported research, a series of experimental studies was conducted to examine the inelastic shear buckling behaviour of the LYP steel plate wall unit under monotonic in-plane load. The stiffness,

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strength, deformation and energy dissipation characteristics of the multi-storey LYP SPSWs were investigated by performing monotonic loading. Based on these studies, design recommendations are proposed for the LYP steel shear wall.

2. Finite element modelling

The finite elements (FEs) analysis calibration study included modelling a steel plate shear wall with the dimensions and properties corresponding to SPSW tested in previous research Vian and Bruneau (2006). In order to validate the numerical representation of the SPSWs, the FEs representation using an FE program has been applied to Vian and Bruneau (2006) model and the results were compared with the experimental results reported by previous research. For this purpose S2 specimen was numerically modelled using an FE program. Figure 1 illustrates S2 specimen dimensions. The frames measured 4000 mm wide and 2000 mm high between member centrelines and consisted of 345 MPa steel members. The infill panels produced by China Steel were 2.6 mm thick, LYP steel plates with an initial yield stress of 165 MPa. The specimens also have a beam-to-column connection detail that includes reduced beam sections at each end.

2.1. *Element definitions*

The entire infill plate and boundary elements were meshed using the S4R shell elements, a four node doubly curved general-purpose conventional shell element with reduced integration and hourglass control. Reduced integration together with hourglass control can provide more accurate results, as long as the provided elements are not distorted (relatively close to being square in shape), and significantly reduce running time, especially in three dimensions. If an hourglass occurs, a finer mesh may be required or concentrated loads must be distributed over multiple nodes. As previous studies (Vian and Bruneau 2006) expressed that using S4R and S4 elements in the finite element program which they used does not interfere the results modelling SPSWs, convergence study on mesh dimension done. The results show that a 50-mm mesh size satisfies the accuracy of the analysis. Figure 2 illustrates the convergence study results obtained.

2.2. *Material definitions*

ASTM A572 Gr. 50 ($Fy = 345$ MPa) steel was used for boundary elements and LYP steel plates with an initial yield stress of 165 MPa for infill plate. Knowing that the infill plate can only yield in tension, and immediately buckles in compression, a unidirectional constitutive stress–strain relationship is used for the infill plate. The cyclic stabilised backbone stress–strain curve was used. Note that these specified nominal stress and strain values were also converted to "true" stress (Cauchy stress) and logarithmic plastic strain.

2.3. *Initial imperfections*

Initial imperfections were applied in the models to help initiate panel buckling and development of TFA. The FE

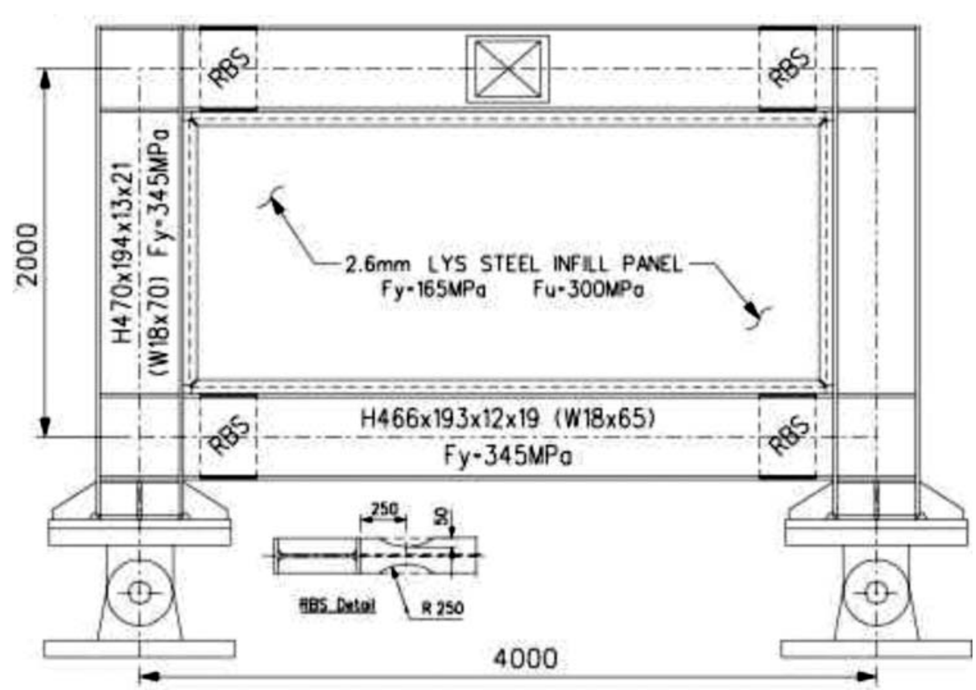

Figure 1. Specimen S2 dimension (Vian and Bruneau 2006).

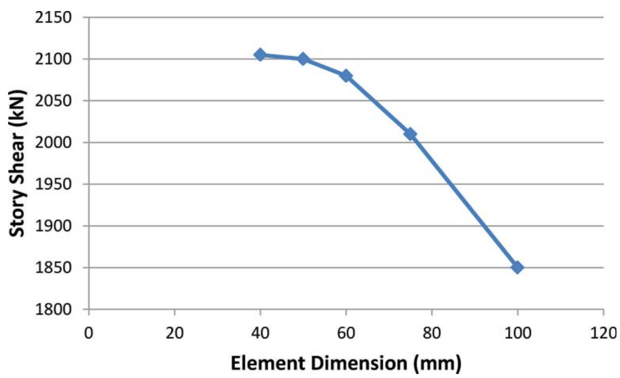

Figure 2. Base shear versus element dimension.

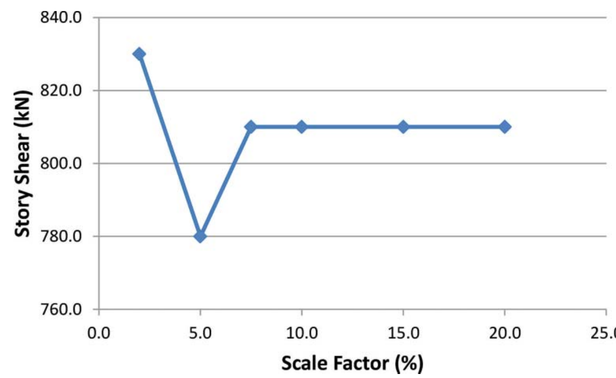

Figure 3. Base shear versus scale factor at drift 0.5%.

program offers two ways to define an imperfection: as a linear superposition of buckling eigenmodes from the displacements of a static analysis or by specifying the node number and imperfection values directly. The first option was chosen for the models described here.

An eigenvalue buckling analysis was first run on the "perfect" structure to request the first 20 eigenmodes. Post-buckling analysis was subsequently run after introducing imperfections in the geometry by adding these buckling modes to the "perfect" geometry where the FE program interprets the imperfection data through nodal displacements. Imperfection scale factor magnitudes corresponded to only a few per cent of the shell thickness. A sensitivity study to investigate the impact of the magnitude of imperfections on analytical results was conducted to determine the proper scale factor to be included in the model to allow a correct post-buckling analysis. A series of post-buckling analyses with a scale factor varying in magnitude from 2% to 20% of shell thickness were subsequently performed and the results are presented in Figure 3. According to this figure, 10% of the shell thickness was used for initial imperfection.

2.4. *Nonlinear analysis*

Risk analysis was used for determining nonlinear results of the FE model. As shown in Figure 4, the FE results are in good agreement with the experimental results.

2.5. *Parametric study*

After verification of the numerical model by experimental results, nine full-scale multi-storey SPSWs were designed using AISC-341 building code (AISC 2005b). The models are categorised into 5-storey, 10-storey and 15-storey groups. Each group consists of three frames which the infill plate steel is different. The steels used for the infill plate are ST 12 ($Fy = 160$ MPa), ST 37 ($Fy = 240$ MPa) and an assumed median steel which yields at 200 MPa. It

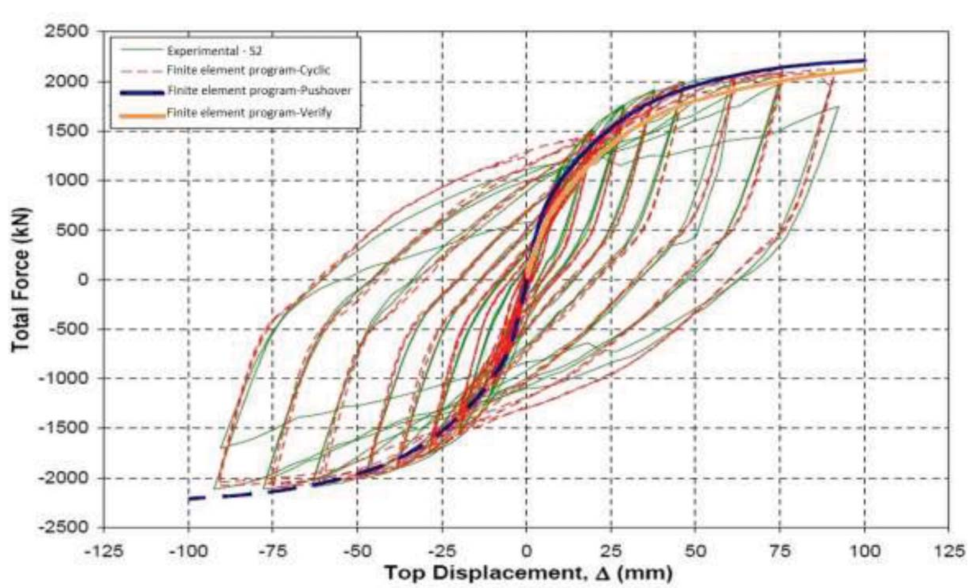

Figure 4. Hysteretic and pushover curves.

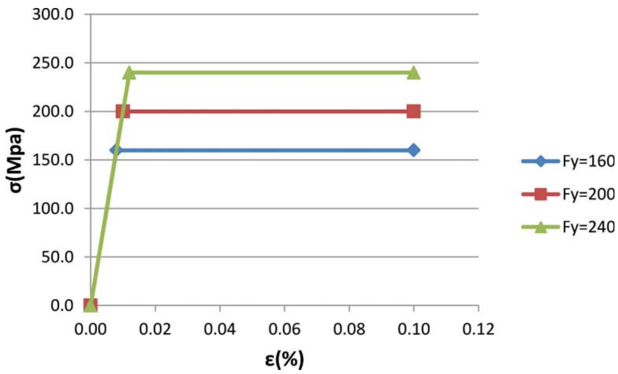

Figure 5. Stress–strain relationship curves of materials.

is assumed that the steels' behaviour is perfectly plastic; the stress–strain relationship curves are illustrated in Figure 5. Frame designed sections are presented in Tables 1–3. The storey height is assumed to be 3000 mm and the frame width 3000 mm.

In this paper, plastic strain, energy dissipation, shear capacity and ultimate displacement of each group are compared. In all groups, models with the ST 37 infill plate are considered as parent models. Figure 6 illustrates plastic strain contours for a 5-storey model. As it is obvious, the ST5-160 model presents the highest plastic strain which leads to most energy dissipation, as presented in Table 4.

Table 1. 5-storey SPSW sections.

Storey	Beam sec	Column sec	ST5-160 web (mm)	ST5-200 web (mm)	ST5-240 web (mm)
5	w12 × 40	w12 × 26	1	1	1
4	w12 × 40	w12 × 53	2	1	1
3	w12 × 40	w12 × 79	2	2	1
2	w12 × 40	w12 × 96	2	2	2
1	w12 × 40	w12 × 96	2	2	2

Table 2. 10-storey SPSW sections.

Storey	Beam sec	Column sec	ST10-160 web (mm)	ST10-200 web (mm)	ST10-240 web (mm)
10	w24 × 76	w24 × 55	1	1	1
9	w24 × 55	w24 × 55	2	2	1
8	w24 × 55	w24 × 104	3	2	2
7	w24 × 55	w24 × 104	3	2	2
6	w24 × 55	w24 × 162	4	3	2
5	w24 × 55	w24 × 162	4	3	2
4	w24 × 55	w24 × 229	5	3	3
3	w24 × 55	w24 × 229	5	4	3
2	w24 × 55	w24 × 335	5	4	3
1	w24 × 55	w24 × 335	5	4	3

Table 3. 15-storey SPSW sections.

Storey	Beam sec	Column sec	ST15-160 web (mm)	ST15-200 web (mm)	ST15-240 web (mm)
15	w30 × 132	w30 × 90	1	1	1
14	w30 × 90	w30 × 90	2	2	1
13	w30 × 90	w30 × 90	2	2	2
12	w30 × 90	w30 × 132	3	2	2
11	w30 × 90	w30 × 132	3	3	3
10	w30 × 90	w30 × 132	4	3	3
9	w30 × 90	w30 × 235	4	4	3
8	w30 × 90	w30 × 235	4	4	3
7	w30 × 90	w30 × 235	5	4	3
6	w30 × 90	w30 × 391	5	4	4
5	w30 × 90	w30 × 391	5	4	4
4	w30 × 90	w30 × 391	5	4	4
3	w30 × 90	w30 × 447	6	5	4
2	w30 × 90	w30 × 447	6	5	4
1	w30 × 90	w30 × 447	6	5	4

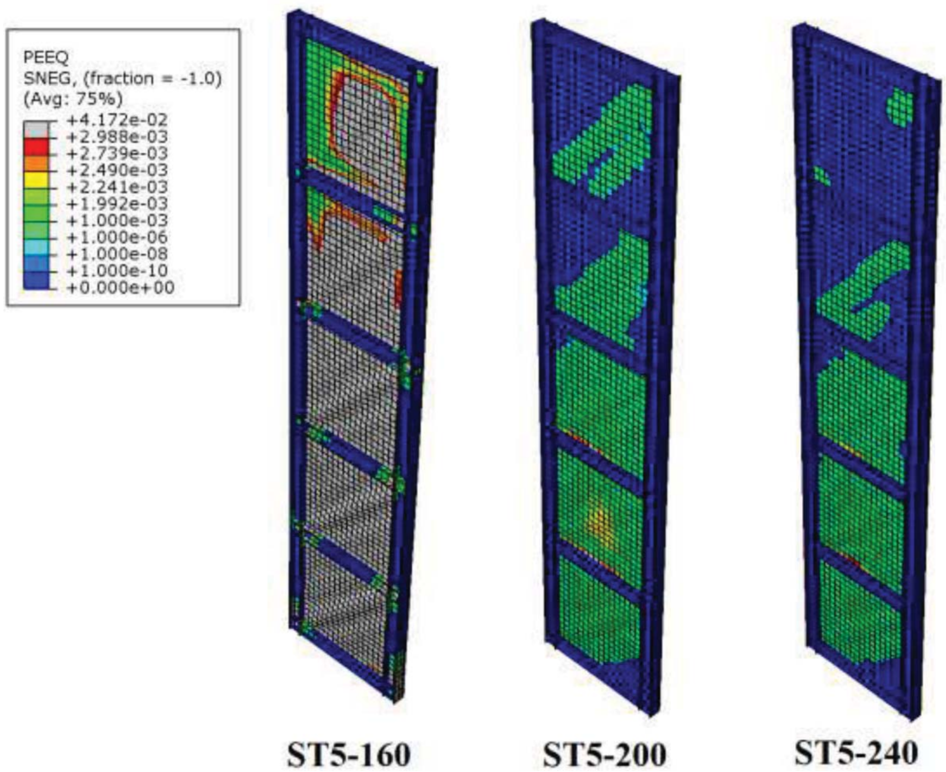

Figure 6. Plastic strain in 5-storey models.

Table 5 and 6 present dissipated energy in 10- and 15-storey models. As it is obvious in these models again, models with LYP steel infill plates dissipated more energy.

It is expected that 10-storey and 15-storey models dissipate two and three times of 5-storey models, but the results show less dissipated energy. It is because in 10- and 15-storey models the upper storey did not yield completely and this situation leads to less energy dissipation.

Table 4. 5-storey models dissipated energy.

Model	ST5-160	ST5-200	ST5-240
Dissipated energy (kN m)	5.91	4.31	3.63
Increase to ST5-240	1.63	1.19	1.00

Table 5. 10-storey models dissipated energy.

Model	ST10-160	ST10-200	ST10-240
Dissipated energy (kN m)	6.06	5.70	5.22
Increase to ST10-240	1.16	1.09	1.00

Table 6. 15-storey models dissipated energy.

Model	ST15-160	ST15-200	ST15-240
Dissipated energy (kN m)	7.95	7.67	6.92
Increase to ST15-240	1.15	1.11	1.00

Using LYP steel leads to thicker infill plates which provides more stiffness for the SPSWs. Figures 7–9 illustrate relative displacement of storeys for 5-storey, 10-storey and 15-storey models, respectively.

As shown, using LYP steel decreases frame displacement caused by lateral loads. In 10-storey models, using ST 12 infill plates reduces storey displacements by up to 16% in comparison to using ST 37. In 15-storey models, the reduction is by about 9%.

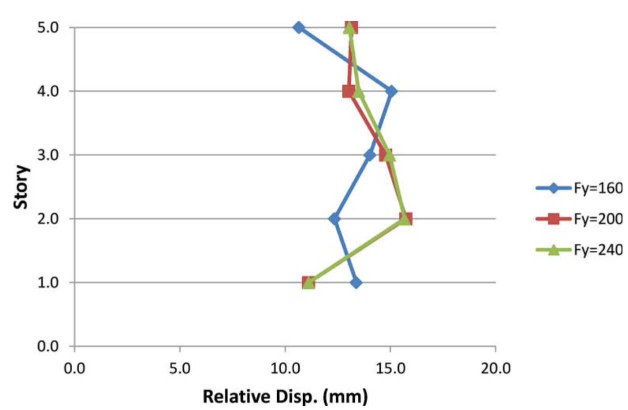

Figure 7. Relative displacement for 5-storey models.

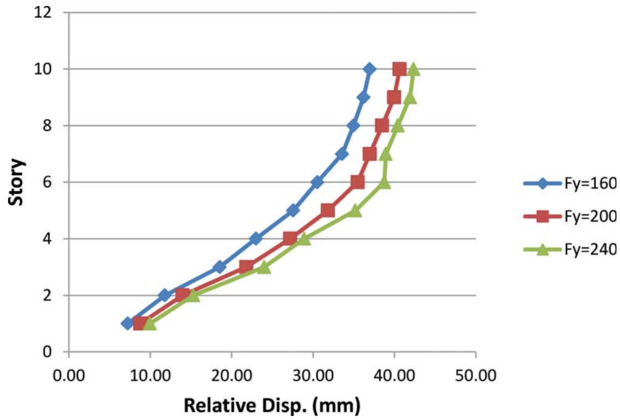

Figure 8. Relative displacement for 10-storey models.

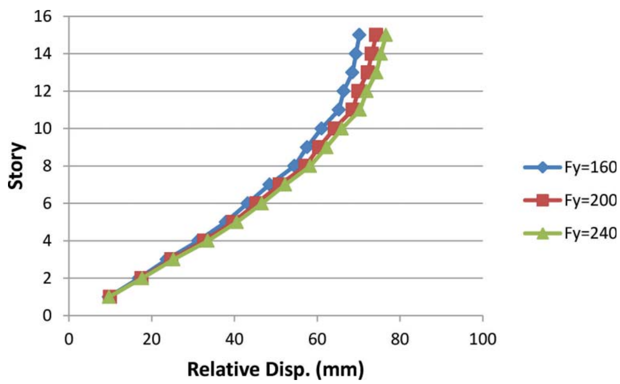

Figure 9. Relative displacement for 15-storey models.

4. Conclusion

The effects of using LYP steel infill plates in SPSWs are studied in this paper. The results showed that using LYP steel increases energy dissipation of the SPSW by up to 63% which increases the advantages of using SPSWs in high seismic zones. The results also represented that using LYP steel will decrease the lateral displacement of buildings which is a concern for tall buildings. Using LYP steel infill plates decreased the lateral displacement of the frames by up to 16%.

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