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Finite Element Analysis of Thin Steel Plate Shear Walls

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***Abstract*—**Steel plate shear walls (SPSWs) in buildings are known to be an effective means for resisting lateral forces. By using un-stiffened walls and allowing them to buckle, their energy absorption capacity will increase significantly due to the post-buckling capacity. The post-buckling tension field action of SPSWs can provide substantial strength, stiffness and ductility. This paper presents the Finite Element Analysis of low yield point (LYP) steel shear walls. In this shear wall system, the LYP steel plate is used for the steel panel and conventional structural steel is used for boundary frames. A series of nonlinear cyclic analyses were carried out to obtain the stiffness, strength, deformation capacity, and energy dissipation capacity of the LYP steel shear wall. The effect of width-to-thickness ratio of steel plate on buckling behavior, and energy dissipation capacities were studied. Good energy dissipation and deformation capacities were obtained for all models.

***Keywords*—**low yield point steel, steel plate shear wall, thin plates, elastic buckling, inelastic buckling, post-buckling.

I. Introduction

STEEL structures have been widely used in the construction of buildings in seismic active areas. Steel shear wall is a possible option for seismic resistance of these structures. A steel shear wall frame consists of column and beam elements augmented by steel infill shear panels, provided over the height of a framing bay. Steel plates can be welded or bolted to the boundary frame. Stiffened and un-stiffened thin steel plate shear walls (TSPSWs) have been introduced as primary lateral load resisting elements in several buildings in the United States and Japan and some of them performed very well through earthquakes in recent years. In early applications of steel plate shear walls, the walls had vertical and horizontal stiffeners. Welding stiffeners can be costly as well as time-consuming. In recent years, the research and testing of specimens have indicated that using post-buckling tension field action of un-stiffened SPSWs leads to very ductile and efficient steel walls.

The idea of using the post-buckling strength of SPSWs was first developed analytically by Thorburn et al [1] and verified experimentally by Timler and Kulak [2]. Experimental studies performed to evaluate the strength, ductility, and hysteretic behavior of such SPSWs designed with un-stiffened infill plates demonstrated their significant energy dissipation capabilities and substantial economic advantages [3-5]. Analytical studies on the shear buckling behavior of multi-story thin steel wall systems have been conducted [6-9]. Driver et al [10-11] developed a nonlinear finite element model for steel plate shear walls. Abouri-Ghomi and Roberts [12] studied the behavior of 16 tests of diagonally loaded steel shear panels. Caccese et al. [13] presented the results of cyclic testing of six 1:4 scale specimens that include one moment-resisting frame, three specimens with various plate thicknesses and moment-resisting beam-to-column connections, and two specimens with shear beam-to-column connections. Elgaaly [14] presented an analytical design model where the plate panels were modeled by a series of equivalent truss elements in the diagonal tension direction.

In recent years, low-yield-point steel (LYP steel) with low yield strength and high elongation properties have been developed and used as steel plate shear walls. The yield stress of this type of steel can be as low as 100 MPa, which is about 40% of the conventional structural steel such as ASTM A36 and more than two times the ultimate elongation. The LYP steel can be used for the steel shear wall system. Using lower yielding strength of steel shear wall, this system lets the shear wall yield prior to the surrounding frame. This system prevents the surrounding frame from collapsing and ensures high energy dissipating capacity before the wall reaches its ultimate strength. This research is aimed at studying a series of analytical models of LYP steel shear walls. The elastic and inelastic behavior of LYP steel shear walls with various width-to-thickness ratios is investigated under cyclic loading.

II. Method of Study

A. Material Properties

The LYP steel plate is used for steel panel and conventional A36 structural steel is used for boundary frame. The mechanical properties of steel used in this study are listed in Table I. The assumed stress–strain relationships of conventional steel and LYP-100 steel used is shown in Fig. 1. The Von Mises yield theory, which is known to be the most suitable for mild steel, is used for the material yield criterion. Ansys multi-linear model and combined isotropic and kinematic hardening is used to simulate the behavior of steel materials under cyclic loads.

TABLE I
MECHANICAL PROPERTIES

Material	Fy (MPa)	Fu (MPa)	Fu/Fy
LYP Steel	100	260	2.6
A36 Steel	250	400	1.60

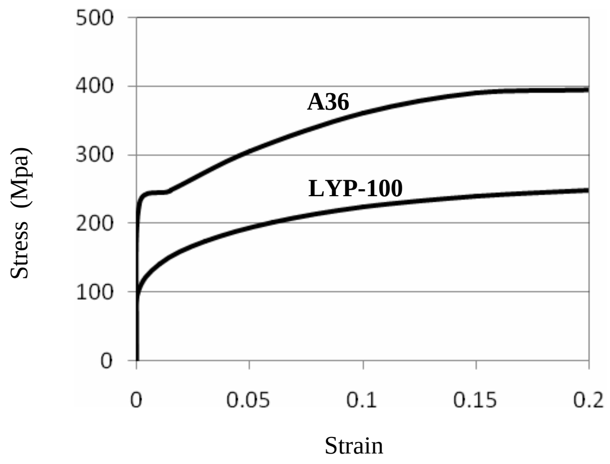


Fig. 1 Assumed stress–strain curves of A36 steel and LYP-100 steel

B. Analytical Models

Six models are designed to study the behavior of LYP steel shear walls under cyclic load that simulate the recursion of seismic excitation. All models with a mesh refinement of 30 × 30 elements resulted in sufficient accuracy, with less than 1% error. Simple connections are adopted for the beam-to-column connections of boundary frames. The LYP steel plates of all models are of square type with width-to-thickness ratio variation from 75 to 200. This is to examine the effect of width-to-thickness ratio on the seismic behavior of steel plate walls. The dimensions of LYP steel plates and beams and columns of all models are shown in Table II. The loading protocol is shown in Table III. Following the loading protocol, all models are subjected to cyclic loading with increasing displacement amplitudes.

TABLE II
DESIGN OF MODELS

Model No.	**Column**	**LYP plate dimensions (mm)**			**b/t**	**h/t**
		Width (b)	**Height (h)**	**Thickness (t)**		
1	H620_305_21_40	3000	3000	40	75	75
2	H620_305_21_40	3000	3000	30	100	100
3	H524_306_21_40	3000	3000	24	125	125
4	H524_306_21_40	3000	3000	20	150	150
5	H432_307_21_40	3000	3000	17.1	175	175
6	H432_307_21_40	3000	3000	15	200	200

TABLE III
LOADING PROTOCOL

Drift angle (rad.)	0.00375	0.005	0.0075	0.01	0.015	0.02	0.03
Number of cycles	3	3	3	3	2	2	2

III. RESULTS

A. Cyclic Behavior

Fig. 2 shows a typical stress distribution (equivalent Von Mises stress) on one side of a panel at drift ratio of 3%. Darker areas show higher stress intensity occurring mostly in the center zone which is commonly known as the tension zone of the panel.

The hysteresis curves for all models are shown in Fig 3. Stable and ductile behavior was observed in all models as shown by the hysteresis loops. Slight pinching occurs as the width-to-thickness ratio increases, which is due to the accumulation of non-recoverable plastic strains. Since the yielding stress of LYP-100 steel plate is about 40% of the steel that is used for the boundary frame, it is seen that the yielding of steel plate occurs far before the yielding of the boundary frame, letting the plastic area spread on the steel plate. This behavior makes the steel plate yield during moderate earthquakes, while the boundary frame remains elastic. During a severe earthquake, the plasticity spreads to the boundary frame.

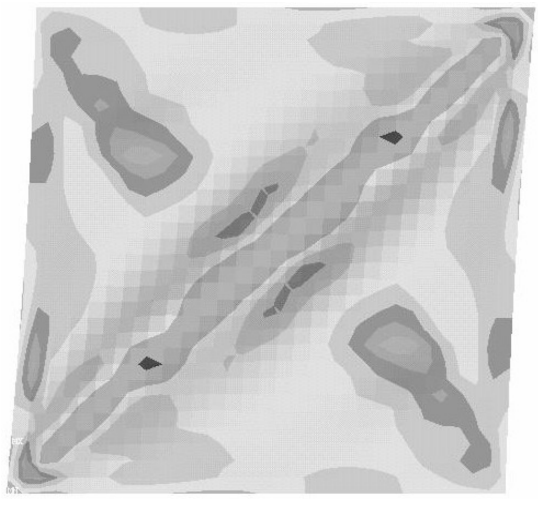
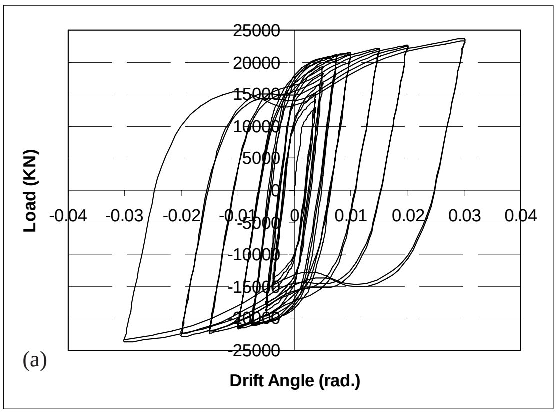
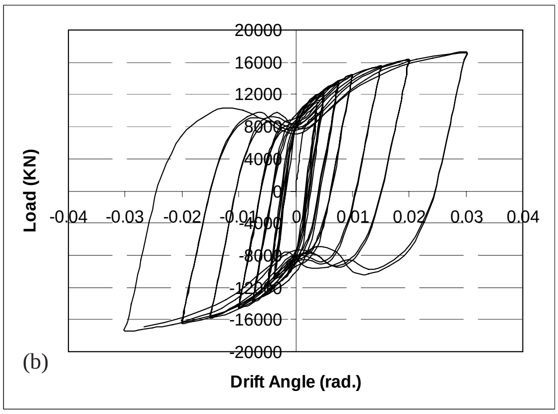
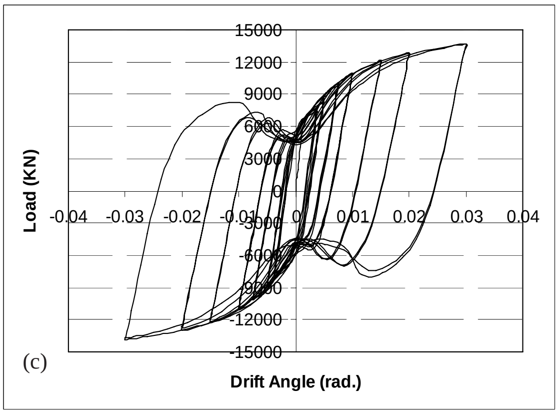
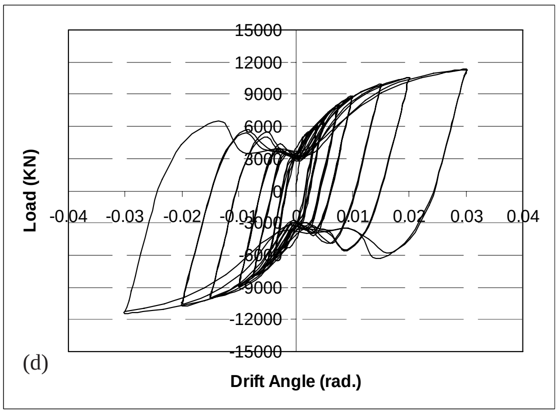


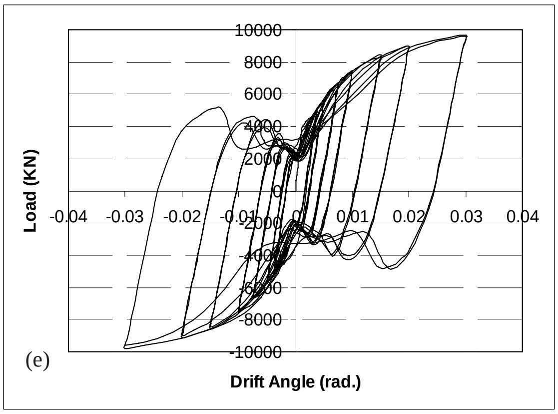
Fig. 2 Stress distribution on one side of a typical panel











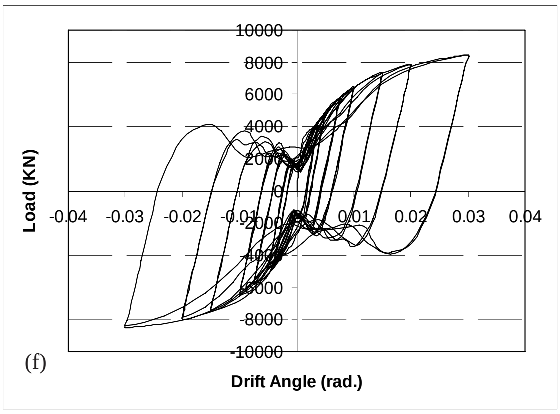


Fig. 3 Hysteresis curves (a) model No.1; (b) model No.2; (c) model No.3; (d) model No.4; (e) model No.5; (f) model No.6

B. Strength and stiffness

The initial stiffness and ultimate strength of all models and the ratio of these values to those of the of model no.6 are shown in Table IV. As expected, models no.1 and no.6 have the highest and lowest strength and stiffness, respectively. The initial stiffness and ultimate strength of SPSW increase as the thickness of the infill plate increases. The stiffness and strength increase in proportional to the increase in thickness.

C. Energy dissipation capacity

From Fig. 3, it is found that all the specimens are able to dissipate energy with stable hysteresis loops. Fig. 4 shows cumulated energy at various numbers of cycles. Values of total energy of models dissipated through hysteresis loops are also listed in Table IV. It is obvious that dissipated energy increases as the thickness of the infill plate increases. Fig. 5 shows how total dissipated energy ratio (ratio of total dissipated energy of a model to that of model No.6) changes with thickness ratio. Due to better inelastic performance and less pinching effect of models with smaller width-to-thickness ratio, these models are able to dissipate much more energy than the models with larger width-to-thickness ratios. For instance, in model No.6 the energy ratio is 4.36 while the thickness ratio of this model is 2.67.

TABLE IV
STIFFNESS, STRENGTH, AND ENERGY DISSIPATION CHARACTERISTICS OF MODELS

Model No.	Thickness ratio	Initial stiffness (KN/M)	Stiffness ratio	Ultimate strength (kN)	Strength ratio	Total dissipated energy	Energy ratio
1	2.67	259e4	2.47	23298	2.77	29400	4.36
2	2	199.3e4	1.9	17221	2.05	18300	2.71
3	1.6	162.4e4	1.55	13669	1.62	13074	1.94
4	1.33	137.1e4	1.31	11294	1.34	9953	1.48
5	1.14	118.5 e4	1.13	9616	1.14	8020	1.19
6	1	104.8 e4	1	8414	1	6740	1

- Energy ratio: ratio of total dissipated energy of a model to that of model No.6
-Strength ratio: ratio of ultimate strength of a model to that of model No.6
-Thickness ratio: ratio of infill plate thickness of a model to that of model No.6
-Stiffness ratio: ratio of initial stiffness of a model to that of model No.6

IV. CONCLUSION

With proper design, the LYP steel shear wall is able to yield at low force levels and dissipate energy via plastic deformation. Significant amounts of ductility are achieved for all models with considerable energy absorption. Reduction in initial stiffness and ultimate strength was seen as the thickness of the infill plate decreased. The increase in stiffness and strength in all models is nearly proportional to the increase in thickness. The energy ratio of all models is always greater than the thickness ratio. Due to better inelastic performance and less pinching effect on models with smaller width-to-thickness ratio, these models are able to dissipate much more energy than the models with larger width-to-thickness ratios. In other words, decreasing the width-to-thickness ratio while all dimensions are kept constant (for instance by using stiffeners) does not increase the initial stiffness and ultimate strength significantly, but energy dissipation capacity does increase significantly.

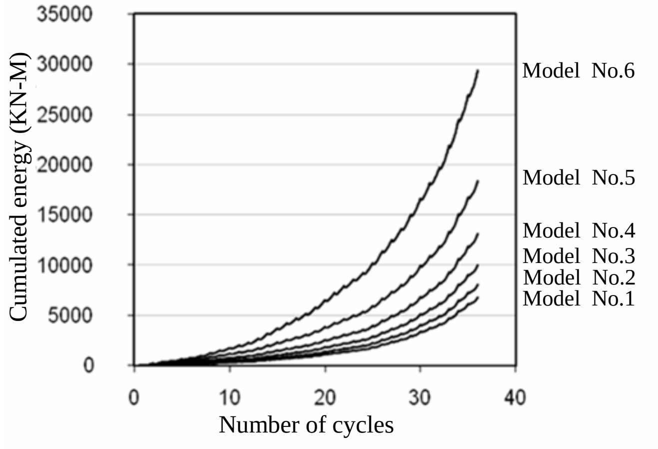


Fig. 4 Cumulated energy dissipated at various number of cycles

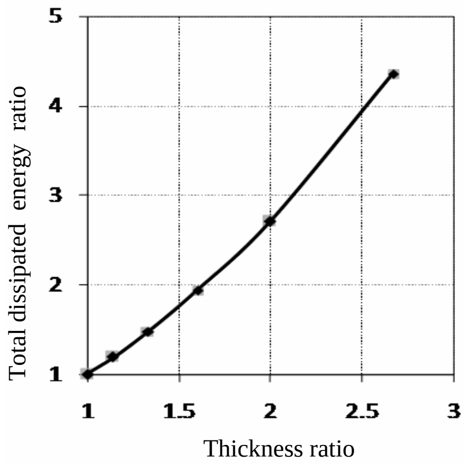


Fig. 5 Energy performance

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