SEISMIC PERFORMANCE ASSESSMENT OF RETROFITTED SPSW SYSTEMS

T. Zirakian\textsuperscript{1} and D. Boyajian\textsuperscript{2}

ABSTRACT

Steel plate shear walls (SPSWs) are efficient lateral force-resisting systems which are used in new and retrofit construction. Based on the findings of the prior studies, it is believed that application of low yield point (LYP) steel with extremely low yield stress as well as high elongation properties can significantly improve the structural behavior and seismic performance of SPSW systems. However, widespread practical application of LYP steel plate shear wall systems requires rather comprehensive and systematic investigations and consequently development of reliable design and retrofitting guidelines. This study focuses on the seismic performance assessment of code-designed SPSW systems retrofitted by unstiffened LYP steel infill plates of various thicknesses. To this end, detailed numerical investigations are made on some key seismic response parameters of multi-story SPSW frames, including drift, acceleration, base shear, and web-plate ductility demands, under the action of earthquake ground motions. The results and findings of this study demonstrate the capabilities of SPSW systems in improving the seismic performance of structures, and particularly reveal the various advantages of use of LYP steel material in advancing the seismic design and retrofit of such lateral force-resisting and energy-dissipating structural systems.

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Seismic Performance Assessment of Retrofitted SPSW Systems

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Steel plate shear walls (SPSWs) are efficient lateral force-resisting systems which are used in new and retrofit construction. Based on the findings of the prior studies, it is believed that application of low yield point (LYP) steel with extremely low yield stress as well as high elongation properties can significantly improve the structural behavior and seismic performance of SPSW systems. However, widespread practical application of LYP steel plate shear wall systems requires rather comprehensive and systematic investigations and consequently development of reliable design and retrofitting guidelines. This study focuses on the seismic performance assessment of code-designed SPSW systems retrofitted by unstiffened LYP steel infill plates of various thicknesses. To this end, detailed numerical investigations are made on some key seismic response parameters of multi-story SPSW frames, including drift, acceleration, base shear, and web-plate ductility demands, under the action of earthquake ground motions. The results and findings of this study demonstrate the capabilities of SPSW systems in improving the seismic performance of structures, and particularly reveal the various advantages of use of LYP steel material in advancing the seismic design and retrofit of such lateral force-resisting and energy-dissipating structural systems.

Introduction

Steel plate shear walls (SPSWs) have been increasingly used in construction of new and retrofit of existing buildings due to their various advantages over other structural systems. Park et al.’s [1] study has shown that unlike conventional reinforced concrete walls and braced frames, well-designed steel plate walls can exhibit high strength as well as large ductility and energy dissipation capacity. In another study reported by Mahtab and Zahedi [2], the relative superiority of steel shear walls to steel cross braces in retrofitting of a 10-story structure has been demonstrated as well. On the other hand, employment of low yield point (LYP) steel plates in shear wall systems has been demonstrated [3,4,5] to be a promising alternative for improving the structural behavior and seismic performance of such lateral force-resisting systems.

In spite of the extensive research work done on SPSW systems, the seismic retrofit of conventional steel shear walls using LYP steel infill plates has not been investigated adequately. By considering the advantages of application of LYP steel with superb material properties

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beneficial for seismic hazard mitigation of structures, this study investigates the seismic performance of code-designed SPSW systems retrofitted by unstiffened LYP steel infill plates of various thicknesses and also examines the effectiveness of a promising retrofitting strategy for improving the seismic performance of conventional steel shear wall systems.

Characteristics of Considered Structural Models

A modified version of the 9-story SAC building designed for seismic and wind conditions in Los Angeles [6] was considered for the purpose of this study. Fig. 1 shows the elevation view of the modified SAC building model with no basement in which fixed column bases and constant story height were considered. As seen in the figure, an interior gravity frame from the SAC building was retrofitted with steel infill plates applied in the middle bay and two-dimensional numerical models of gravity-SPSW frames were developed. P-delta effects caused by gravity loads were also taken into account.

![Figure 1. Elevation view of the modified LA 9-story SAC building [6] model](image)

The SPSW with conventional steel infill plates was designed for a site class D soil and the adjusted maximum considered earthquake spectral response parameters at 0.2 and 1.0 sec periods, $S_{MS}$ and $S_{MI}$, were 2.415g and 1.269g, respectively. Resulting design spectral acceleration parameters at 0.2 and 1.0 sec, $S_{DS}$ and $S_{DI}$, were 1.610g and 0.846g, respectively. The equivalent lateral force procedure, per ASCE 7-10 [7], was used to determine the design seismic loads for the web plates. In design of the SPSW, the conventional steel web plates were assumed to resist the entire story shear demand and the horizontal and vertical boundary elements (HBEs and VBEs) were designed using capacity design principles per AISC 341-10 [8] seismic provisions. The SPSW frame was designed for high-seismic loading and high ductility. ASTM A36 and ASTM A572 Gr. 50 steel material were considered in design of the infill plates and boundary frame elements, respectively. The design results for the gravity [6] and SPSW frames are summarized in Table 1.

Table 2 summarizes the six structural models considered in this study. In the GF-CSPSW model, the steel shear wall was designed by considering conventional steel infill plates. In the GF-LYPSPSW model series, the conventional steel infill plates of the GF-CSPSW model were replaced by LYP steel plates with increasing thickness, while the same code-designed HBEs and VBEs were used. LYP steel shear walls with increasing web-plate thicknesses were considered in this research in order to address the retrofit of new and existing structures using LYP steel shear wall systems with relatively thicker plates compared to those with conventional steel
plates. It is noted that consideration of LYP steel with considerably lower yield stress will result in relatively thicker plates in design of SPSW systems relative to the application of conventional steel material.

Table 1. Design results for gravity and SPSW frames

<table>
<thead>
<tr>
<th>Story/Floor</th>
<th>Gravity Frame [6]</th>
<th>SPSW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beams</td>
<td>Columns</td>
</tr>
<tr>
<td>9/Roof</td>
<td>W16\times26</td>
<td>W14\times48</td>
</tr>
<tr>
<td>8/9</td>
<td>W18\times35</td>
<td>W14\times48, W14\times82</td>
</tr>
<tr>
<td>7/8</td>
<td>W18\times35</td>
<td>W14\times82</td>
</tr>
<tr>
<td>6/7</td>
<td>W18\times35</td>
<td>W14\times109</td>
</tr>
<tr>
<td>5/6</td>
<td>W18\times35</td>
<td>W14\times109</td>
</tr>
<tr>
<td>4/5</td>
<td>W18\times35</td>
<td>W14\times109, W14\times145</td>
</tr>
<tr>
<td>3/4</td>
<td>W18\times35</td>
<td>W14\times145</td>
</tr>
<tr>
<td>2/3</td>
<td>W18\times35</td>
<td>W14\times145</td>
</tr>
<tr>
<td>1/2</td>
<td>W18\times35</td>
<td>W14\times193</td>
</tr>
</tbody>
</table>

Table 2. Considered structural models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Infill plate thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF-CSPSW</td>
<td>Gravity frame with conventional steel plate shear wall</td>
<td>( t_p )</td>
</tr>
<tr>
<td>GF-LYPSPSW1</td>
<td>Gravity frame with replaced LYP steel plate shear wall</td>
<td>1.0 ( \times ) ( t_p )</td>
</tr>
<tr>
<td>GF-LYPSPSW1.5</td>
<td>Gravity frame with replaced LYP steel plate shear wall</td>
<td>1.5 ( \times ) ( t_p )</td>
</tr>
<tr>
<td>GF-LYPSPSW2</td>
<td>Gravity frame with replaced LYP steel plate shear wall</td>
<td>2.0 ( \times ) ( t_p )</td>
</tr>
<tr>
<td>GF-LYPSPSW2.5</td>
<td>Gravity frame with replaced LYP steel plate shear wall</td>
<td>2.5 ( \times ) ( t_p )</td>
</tr>
<tr>
<td>GF-LYPSPSW3</td>
<td>Gravity frame with replaced LYP steel plate shear wall</td>
<td>3.0 ( \times ) ( t_p )</td>
</tr>
</tbody>
</table>

**Details of Numerical Simulation**

Finite element models of the considered structures were developed using ANSYS 14.0 [9] software. A typical wall-frame structural model is shown in Fig. 2. The frame beam and column components were assumed to be laterally braced against out-of-plane deformations. Beam-to-column joints were modeled as moment-resisting connections. Also, constraints were used at story level column nodes to simulate the effect of a rigid diaphragm.

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**Figure 2. Wall-frame structural model**

**Figure 3. Material properties of the steel used**
BEAM188 element was used to model the beam and column components of the frame. The strip model approach was used to represent SPSW behavior, and accordingly the web plates were represented by 15 equally-spaced discrete pin-ended and tension-only strips. The angle of inclination of the tension field was considered as the strip angle, which was taken as 45° in the finite element modeling. The strips were modeled using LINK180 three-dimensional and uniaxial tension-compression truss element. Seismic and lumped masses consistent with the FEMA 355C [6] reported values were placed at each story level on the beam-column intersection nodes, as illustrated in Fig. 2. Lumped masses were modeled using MASS21 point element.

ASTM A36 and LYP100 steel material were considered for the infill plates, and ASTM A572 Gr. 50 steel was employed in modeling of the frame beam and column components. The stress-strain curves and mechanical properties of the steel material are shown in Fig. 3. The von Mises yield criterion was adopted for material yielding, and kinematic hardening rule was incorporated in the nonlinear time-history analyses. Rayleigh proportional damping with a damping ratio of 2% was selected and applied in all seismic analyses. To account for the P-delta effects on the seismic response, gravity loads were initially applied on the two-dimensional structural models prior to the time-history dynamic analysis, and then these loads were kept constant while ground accelerations were applied to the base of the structure. Nonlinear time-history analyses with geometrical and material nonlinearities were conducted in this study.

To verify the adequacy of the finite element strip modeling approach in capturing the dynamic behaviors of the structures, finite element results were validated through comparison with experimental results reported by Park et al. [1]. Modeling details and comparison results are provided in Fig. 4. It is quite evident that the predictions of the strip model agree well with the test results.

![Figure 4. Modeling details and analysis results (3F) for Park et al.’s [1] SC2T specimen](image)

**Characteristics of Selected Earthquake Ground Motions**

A total of eleven earthquake acceleration time histories was selected from the Los Angeles ground motions developed for the SAC steel research project [6] for the time-history response
analyses. Time-history acceleration records were selected in a manner to cover earthquakes with minimum, average, and maximum PGV and PGA values within both 10/50 (10% probability of exceedance in 50 years) and 2/50 (2% probability of exceedance in 50 years) hazard levels. Details of the selected earthquake records are given in Table 3.

Table 3. Details of the selected LA ground motions [6]

<table>
<thead>
<tr>
<th>SAC Name</th>
<th>Record</th>
<th>Earthquake magnitude</th>
<th>PGV (mm/s)</th>
<th>PGA (mm/s²)</th>
<th>Probability of exceedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA02</td>
<td>Imperial Valley, El Centro, 1940</td>
<td>6.9</td>
<td>599.0</td>
<td>6628.8</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>LA06</td>
<td>Imperial Valley, Array #06, 1979</td>
<td>6.5</td>
<td>474.4</td>
<td>2300.8</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>LA11</td>
<td>Loma Prieta, Gilroy, 1989</td>
<td>7</td>
<td>791.4</td>
<td>6524.9</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>LA16</td>
<td>Northridge, Rinaldi RS, 1994</td>
<td>6.7</td>
<td>1007.6</td>
<td>5685.8</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>LA18</td>
<td>Northridge, Sylmar, 1994</td>
<td>6.7</td>
<td>1189.3</td>
<td>8014.4</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>LA19</td>
<td>North Palm Springs, 1986</td>
<td>6</td>
<td>682.7</td>
<td>9994.3</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>LA21</td>
<td>Kobe, 1995</td>
<td>6.9</td>
<td>1427.0</td>
<td>12580.0</td>
<td>2% in 50 years</td>
</tr>
<tr>
<td>LA23</td>
<td>Loma Prieta, 1989</td>
<td>7</td>
<td>737.6</td>
<td>4099.5</td>
<td>2% in 50 years</td>
</tr>
<tr>
<td>LA25</td>
<td>Northridge, Rinaldi, 1994</td>
<td>6.7</td>
<td>1603.1</td>
<td>8516.2</td>
<td>2% in 50 years</td>
</tr>
<tr>
<td>LA28</td>
<td>Northridge, Sylmar, 1994</td>
<td>6.7</td>
<td>1935.3</td>
<td>13041.0</td>
<td>2% in 50 years</td>
</tr>
<tr>
<td>LA29</td>
<td>Tabas, 1974</td>
<td>7.4</td>
<td>710.5</td>
<td>7934.5</td>
<td>2% in 50 years</td>
</tr>
</tbody>
</table>

Finite Element Analysis Results and Discussion

In this section, the performances of the structural models are evaluated by considering some key seismic response parameters including drift, acceleration, base shear, and web-plate ductility demands. Fig. 5 illustrates the finite element analysis results for the seismic-induced peak interstory drift ratios (PIDRs), peak floor accelerations (PFAs), and normalized maximum base shear demands (NMBSDs) of the structural models.

![Figure 5](image)

From Fig. 5, it is evident that the peak interstory drift ratio for the GF-CPSW model is slightly larger than 2.0%, while retrofitting of this system with LYP steel infill plates has limited the drift response to less than 2.0%. Increasing of the web-plate thickness between GF-LYPSPSW1 and GF-LYPSPSW2.5 models has resulted in more reduction of the drift response; nonetheless, the interstory drift ratio has slightly increased in case of the GF-LYPSPSW3 model. This may be attributed to the fact that large plate thicknesses increase the overall system demand on the adjacent vertical boundary frame members and consequently the performance of the structure may be adversely affected due to column instability.
Fig. 5, also, shows that retrofitting of the GF-CSPSW model with LYP steel infill plates favorably lowers the seismic-induced peak floor acceleration in all considered cases. Although increasing of the web-plate thickness results in higher acceleration, the peak floor acceleration in the extreme case, i.e. GF-LYPSPSW3 model with the largest web-plate thickness, is still below that of the GF-CSPSW model.

In Fig. 5, the base shear demands ($V_b$) obtained from the nonlinear time-history dynamic analyses are normalized with the seismic weight ($W_s$) of the structure. From the figure, it is evident that retrofitting of the GF-CSPSW model with LYP steel infill plates is effective in reducing the base shear demand of the SPSW system. However, employment of overly thick infill plates, e.g. in case of GF-LYPSPSW3 model, unfavorably results in relatively large base shear demand.

Studies performed by Zirakian and Zhang [10] and Zhang and Zirakian [11] have shown that retrofitting of a SPSW made of conventional steel, e.g. ASTM A36 and ASTM A572 Gr. 50, with LYP steel infill plates of double thickness can effectively improve the structural behavior and seismic performance of the steel shear wall system. This study, also, intends to examine the effectiveness of such a retrofitting strategy through further investigations. On this basis, the following discussion focusses on the performances of GF-CSPSW and GF-LYPSPSW2 models.

Figs. 6, 7, and 8 show the 9th story drift ratio as well as acceleration, and base shear time histories of the GF-CSPSW and GF-LYPSPSW2 models for the LA06, LA16, and LA23 ground motions (see Table 3), respectively. These figures show that retrofitting of the GF-CSPSW model with LYP steel infill plates of double thickness results in decreased 9th story drift as well as acceleration responses, and also reduced base shear demands of the steel shear wall system.

Figure 6. 9th story drift ratio time histories of GF-CSPSW and GF-LYPSPSW2 models (LA06 g.m.)

Figure 7. 9th story acceleration time histories of GF-CSPSW and GF-LYPSPSW2 models (LA16 g.m.)
In the next step, the web plate ductility demands for all stories of the GF-CSPSW and GF-LYPSPSW2 models are evaluated to further examine the effectiveness of the considered retrofit option for the code-designed and conventional steel GF-CSPSW model. The average values of the maximum web plate ductility ratio for all stories of the two models were obtained by considering the results for all ground motions. The GF-LYPSPSW2-to-GF-CSPSW ductility ratios for all stories are shown in Fig. 9. The maximum ductility ratio for each story was determined from the maximum plastic strain of a strip element with the largest maximum plastic strain value divided by the yield strain.

From the figure, it is evident that the story ductility ratios of the GF-LYPSPSW2 model are larger than those of the GF-CSPSW model except for the 8th and 9th stories. These results demonstrate that use of LYP steel in GF-LYPSPSW2 model with thicker infill plates increases the ductility by 13%, on average, and results in desirable energy dissipation mechanism of the system in which most of the earthquake energy is dissipated through inelastic deformations developed in the web-plate components.

The findings from the above-discussed cases are indicative of effectiveness of application of LYP steel in seismic retrofitting of conventional steel plate shear wall systems. In particular, replacement of conventional steel web-plates with LYP steel plates of double thickness is shown to be an effective retrofitting strategy for enhancing the seismic performance of SPSW systems.
Conclusion

In this paper, the seismic performances of code-designed and retrofitted SPSW frames were investigated using nonlinear time-history analysis of a suite of structural models subjected to eleven earthquake ground motions representing 10/50 and 2/50 hazard levels.

This study shows that retrofitting of code-designed and conventional steel SPSWs with LYP steel infill plates of relatively larger thickness can be quite effective in improving the drift as well as acceleration responses and reducing the seismic-induced base shear demands of such lateral force-resisting systems. Moreover, it is important to note that employment of LYP steel plates with larger thicknesses can improve the buckling stability, energy absorption capacity, and serviceability of such structural systems. Nevertheless, application of overly thick LYP steel plates for retrofitting purposes may adversely affect the seismic response and consequently result in undesirable performance of the SPSW system. Lastly, this study also confirms that application of LYP steel plates with double thickness can be a suitable retrofit option for improving the seismic performance and ductility of conventional-steel SPSW systems.

References