Steel Plate Shear Walls (SPSWs) have proven to be efficient passive energy dissipating systems. Unstiffened SPSWs dissipate energy through tension yielding of web plates and formation of plastic hinges at the ends of horizontal boundary elements. In case of mid- and high-rise buildings, the traditional configuration of SPSW leads to column dimensions larger than the standard sections available commercially. A staggered arrangement of web plates reduces the axial demand in the columns of a staggered-SPSW, which reduces the column sizes. In comparison to a traditional SPSW, staggered-SPSW show reduced interstory drift and a more uniform drift distribution along the height, when subjected to a design based earthquake event. Also, staggered-SPSWs are less prone to a soft- or weak-story mechanism, resulting in better seismic performance. This study performs static and dynamic analyses to evaluate the performance of staggered SPSW during strong earthquake events. 6- and 9-story SPSWs with staggered and conventional configurations are developed in OpenSees. Plate-tearing and flexural hinge strength deterioration are incorporated through strain softening of the material. The modelling technique is validated against published experimental test results. 22-pairs of ground motions, recommended by FEMA P695, are scaled to perform incremental dynamic analysis. The interstory drift response, at design-based-earthquake level, and the fragility curve show that staggered SPSW perform better than their conventional counterpart. For the 6-story conventional SPSW, early failure is observed at the top story, which is not the case when staggered arrangement is adopted. The response of 9-story staggered SPSW is marginally better than the conventional SPSW.
Collapse Analysis of Staggered Steel Plate Shear Wall Systems

A. Verma\textsuperscript{1} and D.R. Sahoo\textsuperscript{2}

\textbf{ABSTRACT}

Steel Plate Shear Walls (SPSWs) have proven to be efficient passive energy dissipating systems. Unstiffened SPSWs dissipate energy through tension yielding of web plates and formation of plastic hinges at the ends of horizontal boundary elements. In case of mid- and high-rise buildings, the traditional configuration of SPSW leads to column dimensions larger than the standard sections available commercially. A staggered arrangement of web plates reduces the axial demand in the columns of a staggered-SPSW, which reduces the column sizes. In comparison to a traditional SPSW, staggered-SPSW show reduced interstory drift and a more uniform drift distribution along the height, when subjected to a design based earthquake event. Also, staggered-SPSWs are less prone to a soft- or weak-story mechanism, resulting in better seismic performance. This study performs static and dynamic analyses to evaluate the performance of staggered SPSW during strong earthquake events. 6- and 9-story SPSWs with staggered and conventional configurations are developed in OpenSees. Plate-tearing and flexural hinge strength deterioration are incorporated through strain softening of the material. The modelling technique is validated against published experimental test results. 22-pairs of ground motions, recommended by FEMA P695, are scaled to perform incremental dynamic analysis. The interstory drift response, at design-based-earthquake level, and the fragility curve show that staggered SPSW perform better than their conventional counterpart. For the 6-story conventional SPSW, early failure is observed at the top story, which is not the case when staggered arrangement is adopted. The response of 9-story staggered SPSW is marginally better than the conventional SPSW.

\textbf{Introduction}

Passive metallic dampers have been used as lateral load resisting devices for decades. They are used to provide adequate stiffness and strength to structures to withstand natural hazards such as wind and earthquake. These dampers dissipate energy by utilizing the post yield behaviour of the constituent materials [1–5]. Unstiffened Steel plate shear walls (SPSW) is one such efficient system. Its high ductility, easy-to-replace ability and cost effectiveness has grabbed the attention of many researchers and engineers. As shown in Fig. 1, an SPSW system comprises of thin steel web plates, surrounded by horizontal and vertical boundary elements (HBE and VBE), which are conventionally provided in the same bay along the height of a frame. It primarily dissipates energy through tension yielding of web plates and through flexural plastic-hinge formation at the HBE ends.

\textsuperscript{1}PhD Research Scholar, Dept. of Civil Engineering, Indian Institute of Technology Delhi, New Delhi, India 110016 (email: abhiverma.civil@gmail.com)
\textsuperscript{2}Associate Professor, Dept. of Civil Engineering, Indian Institute of Technology Delhi, New Delhi, India 110016 (email: drsahoo@civil.iitd.ac.in)

VBEs in SPSWs attract high axial force demands to resist the over-turning forces during a seismic event. This results in an unreasonably high cross-sectional requirement [6]. Seismic design of SPSWs [7], essentially require VBEs to remain elastic during an earthquake event. Failing to which can cause a premature collapse of the entire structure. Thus, reduction of axial demands in VBEs should not only enhance the performance of the system, but also reduce the section sizes, which would make it easier to construct. Recently, a few innovative solutions have been proposed by various researchers to reduce VBE axial demands. Providing outriggers allow the axial force in the VBEs to be transferred to other columns [8], whereas coupling of two SPSW only reduces the force demands in the interior VBEs [9,10]. The conventional practice of providing the web plates in the same bay along the height of a building causes the accumulation of high axial forces in the lower stories. Providing a staggered arrangement of web plates seems to be a simple, yet an effective solution to the problem. Such arrangements, along with reduction of axial forces, can provide greater architectural flexibility. Few such arrangements are illustrated in Fig. 2.

Figure 1. Components of steel plate shear wall [11].

Staggered SPSW (S-SPSW), have shown to have better drift distribution and reduced response to ground motions[12]. This has motivated the authors to further investigate the collapse behaviour of the system. This study considers 6- and 9- story SPSWs with conventional and staggered arrangements. These SPSWs are designed to avoid any overstrength due to unavailability of sections and continuation of the same columns to multiple stories. The SPSWs are then modelled in the open-source simulation software OpenSees [13]. Degradation of strength beyond ultimate capacity is simulated through material softening and results are validated with previously published experimental results. Static pushover analysis is then conducted to evaluate ductility and overstrength. 22-pairs of scaled far-field ground motions suggested by FEMA-P695 [14] are then used to evaluate the dynamic performance of SPSWs at design based earthquake (DBE) level ground motions. Further, incremental dynamic analysis is performed to evaluate the performance of SPSWs for stronger ground motions. Finally, results of the study are presented
and conclusions summarized.

Figure 2. Configurations of conventional and staggered SPSWs (S-SPSWs). SPSW, steel plate shear wall [12].

Design and Modelling of Archetypes

To study the effect of staggering on the behaviour of an SPSW system, two 6- and 9-story buildings are considered. For each building, both conventional and staggered SPSWs are designed. Plan of the buildings are shown in Fig. 4(a). Seismic weight at roof and floor levels are assumed to be 10460 kN and 9710 kN, respectively, for both 6- and 9-story buildings. A constant story height of 3.96 m was assumed. Site specific parameters, $S_s$ and $S_1$ are taken as 1.61$g$ and 0.79$g$, respectively. Response modification factor ($R$) is considered as 7 [20] for all systems. Design base shear for the 6- and 9-story buildings are calculated to be 9049 kN and 13518 kN, respectively. Table 1 summarizes the design parameters for all the four SPSW systems designed in the study. The SPSWs are designed to have a width of 1.15 m. Staggered SPSWs are designed for a reduced design base shear to account for overstrength due to staggering [12]. The base shear reduction factors ($\gamma$) calculated for the two staggered configurations are given in Table 1. Nominal values of material yield strengths of plates and boundary elements are assumed to be 248 MPa and 345 MPa, respectively. The expected yield strength of plates is assumed to be 1.3 times the nominal yield strength as considered in the design. An average value of angle of inclination of tension field ($\alpha$) with respect to the vertical direction is assumed for all the stories. A resistance factor of 0.9 is used for both plates and boundary elements. HBEs are designed to avoid any in-span plastic hinges when the web plates have completely yielded [16]. VBEs are
designed to remain elastic to avoid the development of soft story mechanism [17].

### Table 1. Archetype Details.

<table>
<thead>
<tr>
<th>Archetype</th>
<th>No. of stories</th>
<th>Configuration type</th>
<th>No. SPSW in each loading direction</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>6M</td>
<td>6</td>
<td>Conventional</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>9M</td>
<td>9</td>
<td>Conventional</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>6M-S</td>
<td>6</td>
<td>Staggered</td>
<td>4</td>
<td>0.52</td>
</tr>
<tr>
<td>9M-S</td>
<td>9</td>
<td>Staggered</td>
<td>6</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The computer software *OpenSees* [13] is used to evaluate the seismic performance of the study frames. Only, SPSWs are modelled using the software, as the rest of the frame is not expected to contribute to the lateral resistance of the building. However, gravity columns are considered to take into account the P-delta effect of the gravity loads. Web plates are modelled as tension-only strips inclined at an angle (α) to the vertical in both the directions. The truss element from the *OpenSees* library, with an equivalent area is used to represent the strips. Such a model of SPSW, as shown in Fig. 3(a), is known as a strip model [18,19]. For each model, the values of α at all the stories are calculated separately in accordance with ANSI/AISC 341-10 [7] provisions. Because a small variation in the value of α is found to have no significant impact on the seismic behavior of SPSWs, for simplicity, in any model, an average value of α has been assumed at all story levels. Hysteretic uniaxial material is used to define the tension-only properties of web strips with a strain-hardening ratio of 2%. Stain softening beyond 9εy is also provided to simulate the tearing of web plates, where εy is the yield strain for the web plates. Error! Reference source not found. (b) shows the typical frame joint arrangement for moment-resisting connections.

![Figure 3. Modeling technique adopted in the study showing (a) strip model and (b) arrangement](image-url)
of elements.

The boundary frames are modelled as force-based \textit{BeamColumn} elements in the middle region and as beam with plastic hinges at the two extreme ends. Seventy-two fibers are used to model the I-shaped sections of both the elements considering the axial load–bending moment interaction. Past studies have shown that boundary elements mostly rupture at the extreme ends \cite{20,21}. For this reason hysteretic material is used to provide strength degradation at the extreme ends of the boundary elements, whereas \textit{Steel02} material is provided for the rest of the region. A strain-hardening ratio of 2\% is used for both the materials. The strength degradation is provided up to a distance of one-third of the depth (D) of the section through strain-softening in the hysteretic material. It should be noted that this modelling technique accounts for the plastic hinge formation even beyond D/3, whereas the degradation of strength is restricted in this region only. The modeling technique is validated with previously published experimental results and comparison of story shear of the first story is shown in Fig. 4(a)

\begin{figure}[h]
\begin{center}
\includegraphics[width=\textwidth]{figure4}
\end{center}
\caption{(a) Plan of 6- and 9-story building (b) validation with experimental results.}
\end{figure}

\textbf{Static and Dynamic Analyses}

Static and dynamic analyses are performed for the archetypes to evaluate the performance of the staggered SPSW with respect to the conventional configuration. Firstly, displacement-controlled monotonic pushover analyses are performed to evaluate the overstrength and ductility of the archetypes. Further, dynamic time history analyses are performed using 22-pairs of ground motions suggested in FEMA-P695 \cite{14}. These ground motions are scaled to DBE level. Inter-story drift ratios (ISDR) obtained for the archetypes are compared. Lastly, incremental dynamic analyses are performed and fragility curve for exceedance of 5\% ISDR is plotted.

The results obtained from the pushover analyses are used to plot the normalized base shear for each archetype, against its percentage roof drift. The base shear for each plot is normalized by the design base shear used to design the archetype. These plots, as shown in Fig. 5, are used to evaluate the effective yield roof displacement ($\delta_{y,eff}$), ultimate roof displacement ($\delta_u$),
overstrength ($\Omega_0$) and period based ductility ($\mu_t$), which are tabulated in Table 2. Model 6M shows high overstrength but low ductility. However, model 9M-S has sufficient overstrength but significantly lower ductility than 9M. The low ductility in 9M-S can be attributed to the fact that drift is more concentrated at the bottom 3 stories during the pushover analysis. This results in the early loss of strength of the web plate for these stories, giving rise to a soft story mechanism at the later part of the analysis.

![Figure 5. Base shear versus roof drift obtained from pushover analysis](image)

Table 2. Evaluation of overstrength and ductility.

<table>
<thead>
<tr>
<th>Archetype</th>
<th>$\delta_{y,eff}$ (mm)</th>
<th>$\delta_u$ (mm)</th>
<th>$\Omega_0$</th>
<th>$\mu_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6M</td>
<td>112.7</td>
<td>637.8</td>
<td>3.24</td>
<td>5.66</td>
</tr>
<tr>
<td>6M-S</td>
<td>85.7</td>
<td>637.5</td>
<td>2.37</td>
<td>7.44</td>
</tr>
<tr>
<td>9M</td>
<td>151.0</td>
<td>1026.8</td>
<td>2.53</td>
<td>7.27</td>
</tr>
<tr>
<td>9M-S</td>
<td>147.6</td>
<td>656.4</td>
<td>2.17</td>
<td>4.45</td>
</tr>
</tbody>
</table>

Modal analyses are carried out to obtain the fundamental time periods for the archetypes. The median spectral acceleration of the 22-pairs of normalized ground motions are then scaled to match the design spectrum of each archetype at their respective fundamental time periods. The scaled ground motions are then used to evaluate the performance of the archetypes through time history analyses. Fig. 6 shows a comparison of the median and 84th percentile ISDR for both
staggered and conventional configurations, obtained from the analyses. It can be observed that S-SPSW show reduced values of ISDR than the conventional SPSWs. The median ISDR for the top story reduced from 2.97% to 2.32% and from 2.69% to 2.25% for 6- and 9- story structures, respectively, when staggered configuration is used instead of conventional. For 2 of the 44 ground motions used in the study, collapse is observed at the top story for the archetype 6M.

For a better understanding of the behaviour of the two systems, incremental dynamic analyses (IDA) are performed by progressively scaling up the ground motion until a maximum ISDR of 5% is reached. Analyses to simulate the complete collapse of the structures will be performed in future. The results obtained from the IDA are used to plot the fragility curve for the archetypes. Fig. 7(a) shows the fragility curve for exceedance of maximum ISDR of 5%. For a relative comparison, the spectral acceleration is normalized by the MCE level spectral acceleration for each model. 6M shows a poor performance than the other archetypes as its top story attracts high drifts for more than 80% of the ground motions. The 9-story S-SPSW performs marginally better than its conventional counterpart. Fig. 7(b) show the steel tonnage for the archetypes. Staggered arrangement proves to be marginally more economical in terms of steel usage.

![Figure 6. Inter story drift ratios (ISDR) for DBE level ground motions.](image)

![Figure 7. (a) Fragility curves for 5% drift exceedance (b) Steel tonnage](image)
Conclusions

The following conclusions can be made from the study.

1. The procedure used in the present study, to design the staggered SPSWs [12], results in SPSWs with sufficient overstrength.
2. The period based ductility for 9-story SPSW, calculated through static pushover analysis, reduced considerably from 7.27 to 4.45 on staggering of web plates. This can be attributed to the reduction of ultimate roof drift due to concentration of drift in the lower stories.
3. No negative effect of reduced ductility of the staggered 9-story SPSW is observed in the time history analysis. The fragility performance for 5% drift exceedance for both the configurations for 9-story SPSWs is similar.
4. 6-story conventional SPSW is found to have drift concentrated in the top story, which results in its poor seismic performance. However, staggering eliminates this issue and enhances its performance.

References

15. ASCE. Minimum design loads for buildings and other structures. ASCE/SEI 7–10; 2010.


