INVESTIGATION ON SEISMIC BEHAVIOR OF CONCRETE FILLED DOUBLE-STEEL-PLATE (CFDSP) SHEAR WALL

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ABSTRACT

Shear wall systems are one of the common lateral-load resisting systems in high-rise buildings. A new type of composite shear wall representing a higher performance than ordinary shear walls is introduced in this paper. The CFDSP wall is composed of a concrete body and steel plates on the either side of it. The steel plates are attached to concrete panel face using shear connectors welded to them. To obtain the mechanical properties of this new CFDSP wall, numerical studies were performed using ABAQUS software and the results were verified by experimental results. Concrete Damage Plasticity and kinematic hardening were used to define the behavior of concrete and steel plates, respectively. Three types of shear connectors with variable distances were modeled to find the best shear connector conditions. Results revealed that due to well connection between the steel plates and concrete panel, no buckling occurred in steel plates. This way the steel plates could perform desirably during the loading process.

Increasing steel plate thickness was more effective in wall capacity enhancement than concrete panel thickness. Furthermore, numerical studies showed that the concrete panel has a determinate role in lateral bearing capacity, if the ratio of compressive strength of concrete to its unit weight is greater than 10. Finally, the optimum values of the steel plate and concrete panel thickness and strength, and shear connector characteristics were reported.

Keywords: Shear wall, Shear connector, Concrete-damage-plasticity, concrete compressive strength

1. INTRODUCTION

Reinforced concrete shear walls are used as lateral load resisting systems for many years. Since the 80s, steel plate shear walls have been considered as a new lateral load resisting system. Steel and RC walls have some disadvantages that using composite shear walls consisting of a steel plate and concrete panel on one or both sides can override them. There are three types of composite shear walls:

1. A steel plate with a concrete panel on one side (SPC) (Fig. 1-a)
2. A steel plate with concrete panel on both sides of the steel plate (SPDC) (Fig. 1-b) and
3. Concrete filled double steel plates (CFDSP) (Fig. 1-c).

Wright et al. [1] conducted some research on CFDSP shear walls under different loading conditions. He found that as steel plates provide similar characteristics to the conventional framework for concrete casting, they play the main role in lateral load bearing of composite shear walls. In 1998, a new type of CFDSP shear wall was introduced by Astaneh-Asl [2] that had a gap between the wall and columns (Fig 2-a). He found that the concrete panel is very effective in steel plate buckling prevention. In 2011, Dan et al. [3] studied the nonlinear behavior of composite shear walls consisting of vertical encased profiles. He revealed the superior performance of those walls when subjected to service or ultimate loads (Fig 2-b). He used high strength concrete to avoid compression failure in the concrete panel prior to yielding of steel sections, leading to slightly higher resistance and ductility in comparison to lower concrete strengths.

In 2013, Nie et al. [4] investigated the seismic behavior of CFDSP shear walls (Fig 2-c). They announced that the new detailed composite shear walls with high strength concrete exhibit large lateral

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deformation capacity. Zhou et al. [5] analyzed composite shear walls with varying parameters such as the reinforcement ratio of RC shear walls under cyclic load. Their results indicated that steel plates and the spacing of shear studs have an important effect on shear capacity and ductility of shear walls. In 2015, Epakachi [6] studied on flexural behavior of composite shear walls. He presented a simplified procedure to calculate the monotonic force–displacement response of this wall. In this research, several numerical models were developed and analyzed in ABAQUS to investigate the effects of different shear connectors and mechanical properties of concrete and steel plates on the monotonic and seismic behavior of CFDSP shear walls (Fig. 3). Strength and deformation capacities of CFDSP shear walls are extracted and compared to each other. After all seismic behavior of the most efficient CFDSP shear wall is presented.

![Composite Shear wall types a)SPC, b)SPDC, C)CFDSP](image)

Figure 1. Composite Shear wall types a)SPC, b)SPDC, C)CFDSP

![Composite Shear wall types](image)

Figure 2. (a) Astaneh-Asl composite shear wall [2], (b) Nie and et al composite shear wall [4], c) Epakachi et al composite shear wall [5]
2. NUMERICAL ANALYSIS

For the nonlinear finite element modeling of CFDSP walls, the general purpose finite element software ABAQUS, was used. The CFDSP walls were subjected to pushover loading at their tops. The obtained load-displacement curves were used to define the optimum concrete compressive strength, steel yield stress and shear connector type and distance. These final parameters were used in the model subjected to cyclic loading.

2.1 Materials and Method

Using appropriate properties of concrete compressive and steel tensile strengths are important to reach desirable ductility and stiffness in composite shear walls. Concrete grades of C16, C20, C25, and C30 and steel plates of ASTM LYP-100, A653-DX51d, A620, A36, and A588 were selected to evaluate their effects on wall behavior. Concrete Damage Plasticity (CDP) and kinematic hardening were used for definition of the concrete panel and steel plates mechanical properties, respectively. Concrete material properties defined in ABAQUS models are presented in Table 1 [7]. Stress-strain curves of LYP-100, A36, and A588 are shown in Fig. 4 and Fig. 5, respectively.

Friction between the concrete panel and steel plates was assumed similar to the internal friction of concrete and as the buckling of steel plates was prevented by the concrete panel, it was neglected in the modeling process. A Node To Surface constraint was used to tie one face of the steel plate to shear connectors embedded in the concrete panel.

Beam elements (B31), Eight node solid elements with full integration (C3D8), and Four node shell elements with full integration (S4) were selected for meshing of shear connectors, infill concrete, and steel plates, respectively.

Pushover behavior of CFDSP shear walls was investigated using the Dynamic/Explicit step in ABAQUS. To ensure that analysis is performed quasi-statically, "smooth step" loading was used and the kinematic to internal energy ratio was kept to minimum (under 5% for the most of analysis).
### Table 1. Properties of Concrete for Concrete-Damage-Plasticity model

<table>
<thead>
<tr>
<th>Concrete grade</th>
<th>Compressive strength ($f'_c$) MPa</th>
<th>Eccentricity of the plastic potential surface $\varepsilon$</th>
<th>Initial biaxial compressive yield stress to initial uniaxial compressive yield stress</th>
<th>Ratio of the second stress invariant on the tensile meridian to compressive meridian at initial yield ($k_t$)</th>
<th>Mode I tensile fracture energy of concrete ($G_t$ kN/m)</th>
<th>Angle of dilation ($\psi$)</th>
<th>Modulus of elasticity (E Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>16</td>
<td>0.1</td>
<td>1.16</td>
<td>0.67</td>
<td>41.687</td>
<td>0.2</td>
<td>30</td>
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<tr>
<td>C20</td>
<td>20</td>
<td>0.1</td>
<td>1.16</td>
<td>0.67</td>
<td>48.735</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>C25</td>
<td>25</td>
<td>0.1</td>
<td>1.16</td>
<td>0.67</td>
<td>56.974</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>C30</td>
<td>30</td>
<td>0.1</td>
<td>1.16</td>
<td>0.67</td>
<td>64.730</td>
<td>0.2</td>
<td>30</td>
</tr>
</tbody>
</table>

### Table 2. The ABAQUS models variables

<table>
<thead>
<tr>
<th>Model code</th>
<th>Composite shear wall dimensions (mm$^2$)</th>
<th>Concrete panel thickness ($t_c$ mm)</th>
<th>Concrete compressive strength ($f'_c$ MPa)</th>
<th>Steel plates thickness ($t_s$ mm)</th>
<th>Steel yield strength ($f_y$ MPa)</th>
<th>Metal international code</th>
<th>Shear connector type</th>
<th>Shear connector distance (l, mm)</th>
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</thead>
<tbody>
<tr>
<td>CFDSP 1</td>
<td>3000*3000</td>
<td>100</td>
<td>16</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>stud</td>
<td>200</td>
</tr>
<tr>
<td>CFDSP 2</td>
<td>3000*3000</td>
<td>100</td>
<td>16</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>stud</td>
<td>200</td>
</tr>
<tr>
<td>CFDSP 3</td>
<td>3000*3000</td>
<td>100</td>
<td>20</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>stud</td>
<td>200</td>
</tr>
<tr>
<td>CFDSP 4</td>
<td>3000*3000</td>
<td>100</td>
<td>25</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>stud</td>
<td>200</td>
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<tr>
<td>CFDSP 5</td>
<td>3000*3000</td>
<td>100</td>
<td>30</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>stud</td>
<td>200</td>
</tr>
<tr>
<td>CFDSP 6</td>
<td>3000*3000</td>
<td>100</td>
<td>30</td>
<td>5</td>
<td>140</td>
<td>A653-DX 51</td>
<td>stud</td>
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<td>100</td>
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<td>5</td>
<td>210</td>
<td>A620</td>
<td>stud</td>
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<td>30</td>
<td>5</td>
<td>360</td>
<td>A588</td>
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<td>100</td>
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<td>5</td>
<td>240</td>
<td>A36</td>
<td>UNP</td>
<td>200</td>
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<td>CFDSP 10</td>
<td>3000*3000</td>
<td>100</td>
<td>30</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>bended rebar</td>
<td>200</td>
</tr>
<tr>
<td>CFDSP 11</td>
<td>3000*3000</td>
<td>100</td>
<td>30</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>UNP</td>
<td>150</td>
</tr>
<tr>
<td>CFDSP 12</td>
<td>3000*3000</td>
<td>100</td>
<td>30</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>UNP</td>
<td>300</td>
</tr>
<tr>
<td>CFDSP 13</td>
<td>3000*3000</td>
<td>100</td>
<td>30</td>
<td>5</td>
<td>240</td>
<td>A36</td>
<td>UNP</td>
<td>500</td>
</tr>
</tbody>
</table>
2.2 Analysis Verification

Experimental data provided by Nie [4] on a new detailed CFDSP wall applicable in super high-rise buildings (Fig 2.b) were used to verify modelling in numerical analysis. The mentioned CFDSP wall is composed of concrete filled steel tubular (CFST) columns at the two boundaries and a concrete filled double-steel-plate wall body which is divided into several compartments by vertical stiffeners transversely connected by distributed batten plates. To enhance concrete ductility, high-strength concrete in each compartment of the wall body is confined by the surrounding steel [4]. Three modeling techniques were compared so that the best technique for connecting steel plates to concrete can be determined (Fig 6). These techniques are as follows:

1. Connecting the shear connectors embedded in the concrete panel to steel plate, using Tie contact (Type 1- Line with diamond in Fig.6).
2. Considering an equivalent thicker steel plate instead of the real plate and shear connectors assembly and using Tie contact to connect the equivalent plate to the concrete panel (Type 2- Line with circle in Fig.6).
3. Considering the aforementioned equivalent plate; connecting the equivalent plate to the concrete panel; "Hard Contact" in plumb direction and friction contact similar to internal friction of concrete in
tangential direction (Type 3- Line with triangle in fig.6).
As it can be seen in fig.6, type 3 has the best compatibility with Nie’s results. Stress distribution of type 3 and the Nie's numerical model obtained in ABAQUS are shown in figure 7. Based on this figure, the failure region in experimental study matches with the stress distribution in numerical model.

![Figure 6](image6.png)

Figure 6. Comparison of lateral load-displacement curves (Nie et al. experimental results [4] vs. developed numerical models)

![Figure 7](image7.png)

Figure 7. a)Nie’s experimental study on composite shear wall [4] b) numerical analysis on Nie’s composite shear wall with type 3 of steel plate and concrete panel contact

2.3 Analysis Results
ABAQUS model variables are listed in Table 2. To study the effect of compressive strength of concrete, load-displacement curves of CFDSP1, CFDSP2, CFDSP3, and CFDSP4 models are compared in Fig. 8. Furthermore, to investigate the role of steel plate yield strength, load-displacement curves of CFDSP4, CFDSP5, CFDSP6, CFDSP7, and CFDSP8 models are shown in Fig. 9. Three types of shear connectors (studs, UNP profiles, and bended rebars) were modeled to evaluate their effect on steel to concrete panel connection and their relative load-displacement curves of CFDSP4, CFDSP9, and CFDSP10 are reported in Fig. 10. Furthermore, the distance between shear connectors were changed and the load-displacement curves of CFDSP9, CFDSP11, CFDSP12, and CFDSP13 were compared in Fig. 11 to obtain the suitable distance that makes the steel plates and concrete panel a uniform body. After obtaining the desirable values for concrete compressive strength, steel yield stress and shear connector type and distance, a composite shear wall with all the selected parameters (CFDSP12) was modeled and subjected to seismic load (Fig. 12).

![Figure 8. Comparison between four types of concrete compressive strength in composite shear wall response.](image)

Fig. 8 illustrates that increasing the concrete compressive strength has a minor effect on the load-displacement response of the CFDSP walls until using high-strength concrete. The first collapse mode of the CFDSP wall is cracking and spalling of the concrete panel, so the tensile strength of concrete is more important. By using high-strength concrete, the collapse of the CFDSP wall will occur after yielding of the steel plate and makes it possible to consider the concrete compressive strength in the design of the CFDSP wall.
Fig. 9 indicates that there is a direct relationship between steel plate strength and the lateral load resistance capacity of the composite shear wall. The increase in lateral load bearing capacity of CFDSP5 is higher than the anticipated capacity based on the steel plate strength ratios (215 to 175 kN). This increase in load bearing of the composite shear wall means that using more ductile steel (like LYP-100) enhances the capacity of the composite shear wall.

Figure 10. Comparison between three types of shear connectors in composite shear wall response.
Figure 11. Comparison between four types of shear connector distance in composite shear wall response.

Figure 12. Hysteretic behavior of the CFDSP 12 composite shear wall

Figure 13. Hysteretic behavior of the CFDSP 2 composite shear wall
Fig. 12 shows that the CFDSP12 model can reach 12 mm displacement without reduction in its strength. The model can reach to 14 mm displacement while losing 45% of its strength. The CFDSP12 model has arranged loops until reaching 12 mm displacement and after that the loops crush to a lower strength. Fig. 12 reveals that seismic response of the CFDSP wall is similar to concrete shear walls, so it can be noted that the seismic performance of CFDSP walls are dependent on concrete seismic behavior.

To prove the superiority of CFDSP 12’s seismic performance over other configurations, figure 13 which represents the cyclic behavior of CFDSP 2 is presented. As it can be seen, CFDSP 12 develops larger loops and shows better performance regarding to strength and deformation capacity.

3. CONCLUSION

The CFDSP shear wall is a high performance alternative to conventional RC walls to be used in tall buildings. This type of shear wall was examined having various characteristics and being subjected to various types of loading (axial, cyclic, impact, thermal, and combined) in some recent researches. In this research, pushover behavior of the CFDSP shear walls were investigated to obtain optimum values for concrete compressive strength, steel yield stress, shear connector type and shear connector distance. Then, the seismic behavior of the shear wall with selected parameters was studied.

1- Concrete compressive strength is not as effective as steel yield strength in lateral load resistance capacity of the shear walls until high-strength concrete is used. In that situation, the CFDSP wall capacity is affected by concrete compressive strength and the collapse mode of the CFDSP wall is changed.

2- Yield strength of steel plays a major role in lateral load bearing capacity of CFDSP shear walls.

3- UNP shear connectors showed the best connection ability between steel plates and the concrete panel in comparison to studs and bended rebars.

4- It was observed that placing shear connectors at a distance of three times of concrete panel thickness would result in better lateral load bearing behavior of CFDSP walls.

5- In cyclic loading the CFDSP12 model can reach 12 mm displacement without reduction in its strength. With the displacement increased, the model loses 45% of its strength reaching 14 mm displacement.

6- The seismic behavior of the CFDSP shear wall is affected by concrete seismic behavior.

7. REFERENCES


[8] By Eiichiro Saeki, Mitsuru Sugisawa, R'Tanemi Yamaguchi, and Akira Wada; "Mechanical properties of low yld point steels", journal of materials in civil engineering, 1998