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Investigation of the beams and columns connection with infill plate on the structural behavior of the steel plate shear walls

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Abstract

Steel plate shear walls are commonly used as structural lateral load resisting load systems in space-constrained areas. Many studies indicated that the implementation of the steel plate shear walls improves the ductility, stiffness and ultimate strength of the structure for which the interconnection of the steel infill plate with boundary members has a significant role. The typical connection of the infill shear plates to the boundary elements has a high-level fixity despite the general convenient construction procedures. In this study, the connection of the infill plates to the boundary elements are precisely investigated by establishing more than 21 computational models after verifying the modeling methodology. The structural performance of the partially connected plates with different commonly used connections types are evaluated and compared to the corresponding conventional fully connected infill plate systems. It is shown that column-only connected infill plate shear wall reduces the structural lateral load resisting capacity tangibly more than beam-only connected infill plates due to limited tension field action development. In addition, results indicated that systems with partial infill plate connection and connectivity ratio of 80% or more generally have similar structural performance compared to conventional systems with full connected infill plates.

Key words: Steel plate shear wall, infill plate connection, boundary elements, energy dissipation.

1. Introduction

Steel plate shear walls are commonly implemented in high-rise buildings for improving the structural seismic behavior. The steel plate shear walls are designed based on the cantilever wall system consisting vertical steel plate connected to surrounding boundary element members. Studies have indicated that these systems show high stiffness, desirable energy dissipation capability, efficient use of the space and adequate ductility for use in various structural applications [1-4]. In general, the total of weight of the structure with steel plate shear wall are lighter than the corresponding similar structures having other types of lateral load resisting systems, making the steel plate shear wall a desirable system to be used in regions of high seismicity. Use of steel plate shear wall in structures with significant importance, in high-rise buildings for providing efficient lateral load resisting system and in residential applications resulted in a better implementation of the space, lower demand force applied to foundations, exceptional performance under earthquakes, reducing the total weight of the structures, and convenient construction procedures [4].

Under lateral cyclic loading conditions, the steel plate shear wall undergoes in-plane and out-of-plane deformations. For this system, the buckling occurs at the early stages of deformation due to slenderness of the infill panel. Subsequently, the infill plate fold in out-of-plane direction making diagonal tension field action parallel to the principle tensile stresses, which leads to the post-buckling resistance capacity. Several studies indicated that the post-buckling strength of these walls is highly depended on the tension field action development, which is completely affected by the infill plate interconnectivity with boundary elements. In addition, the presence of the adequate flexural stiffened boundary elements leads to uniform tension field action development; therefore, the total capacity of the of the infill plate is incorporated [3, 4]. It is noted that in innovative steel plate shear walls (e.g. corrugated steel plate shear wall, SPSWs with opening, shear walls with strategic cutouts, etc.) the tension field actions were observed to be deformed partially or with different diagonal folding angles as the principle tensile stresses conditions for these applications were different from the conventional steel plate shear wall systems [3]. To reduce the demand forces on the columns, the infill plate is detached from the columns which is proposed in recent studies. The detachment of the infill steel plate leads to lower demand forces generated by tension field action on columns; hence, smaller boundary element sections are required [5]. However, through laboratory investigation it is shown that the detachment of the infill generally decreases the system ductility and energy dissipation capability, which needs to be more investigated in details [5].

The importance of the infill plate connection to the boundary elements is emphasized in previous studies. Hosseinzadeh and Tehranizadeh [6] investigated the shear wall systems with stiffeners. They concluded that infill plate if appropriately connected to the boundary elements is able to improve the overall system behavior for having adequate ductility and energy dissipation capability; however, proper interconnection of the infill plates leads to an efficient interactive frame performance after the plate reaches to the post-buckling stage. Farzampour et al. [4] showed that the use of the reduced beam section with appropriate connected infill panel effectively moves the plastic hinges to the areas with less stress concentration in steel plate shear walls indicating less protentional for micro-crack propagation at the beam-column joint areas. In addition, the premature column failure is avoided in previous applications by implementing simple beam-to-column connection with the infill plates connected only to the beams. The dual characteristics of the steel plate shear wall consisting of the frame and infill plate could be split up as distinctive subsystems, which is highly dependent of the appropriate infill-to-boundary-member connection quality [6].

In this study, the infill plate interconnection with boundary elements are investigated considering different typical connection procedures. For this purpose, the finite element modeling methodology is initially established and validated based on two laboratory tests. More than 21 computational models are developed based on the verified specimen, and the infill plate interconnectivity ratio is estimated for each model to investigated various infill plate interconnections.

2. Verifications of Modeling Methodology

laboratory test used for the verification purposes is conducted by Sigariyazd et al. [2] which shown in Figure 1. The studied shear wall system is a one-story, and one-bay system with 2100mm length and 1200 mm height. The 1.5 mm thick infill plate yielding stress and ultimate stress are 222 MPa and 315 MPa, respectively. In addition, the yielding stresses for beams and columns are 254 MPa and 280 MPa, and the ultimate stresses are 383 MPa and 423 MPa, respectively. The loading is applied at the top beam following the ATC 24 cyclic protocol typically used for lateral force resisting systems investigations. The reduced integration four nodded shell elements are implemented for establishing the computational models due to appropriate features in capturing the buckling inside of the infill plates. The mesh sensitivity analysis is conducted to identify the 30 mm fine mesh size for all the SPSW members and infill plate considering the geometrical and material nonlinearity. It is noted that the imperfection is considered for FE modeling based on the 0.01 out-of-plane displacement corresponding to the first buckling mode. The backbone and structural behavior of the test are obtained by finite element modeling methodology with more 95% accuracy which are shown in Figure 2 and Figure 3, respectively.

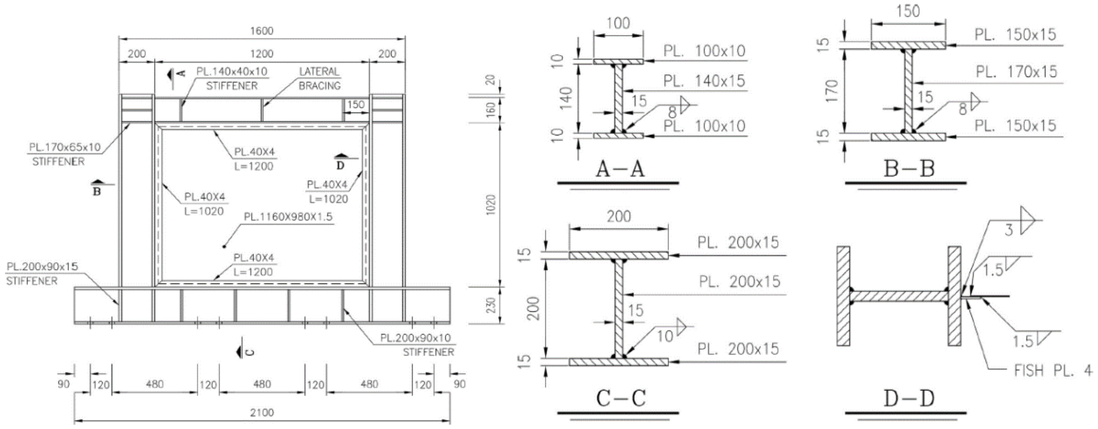


Figure 1: The details of the first laboratory test considered for verification of the computational study [2]

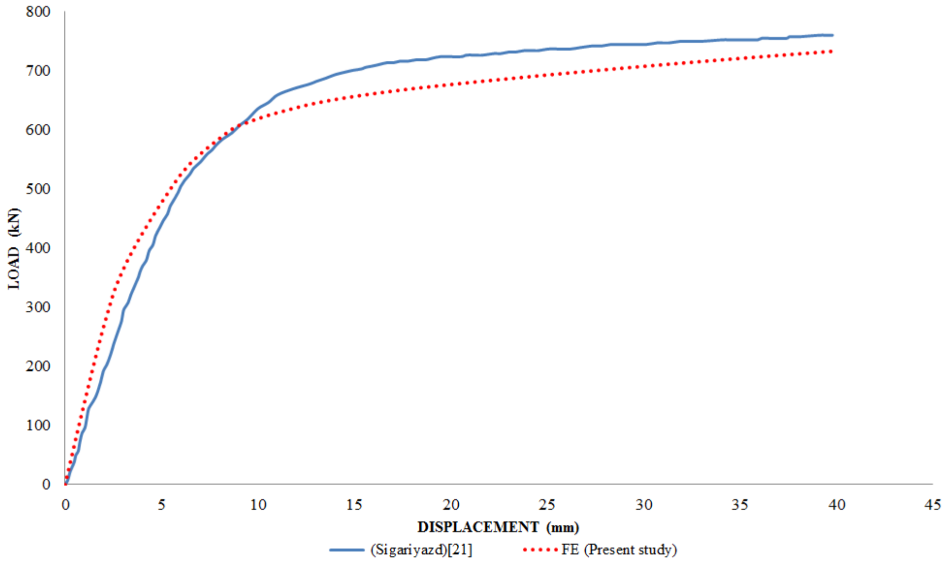


Figure 2: The pushover results showing more than 95% accuracy of the FE methodology

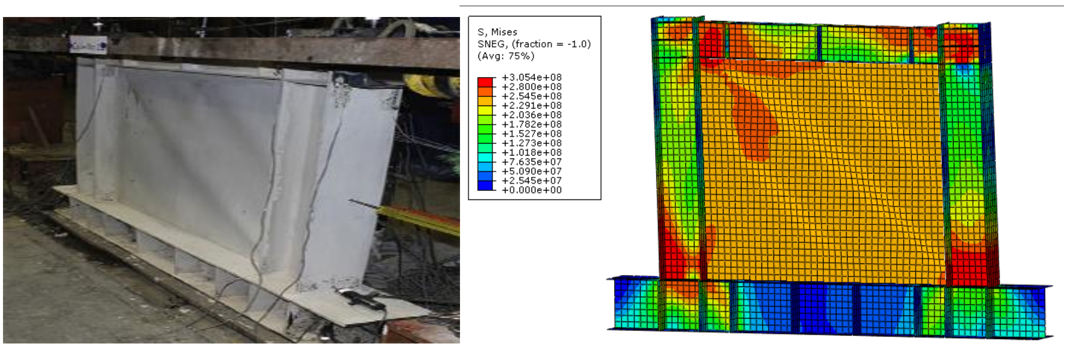
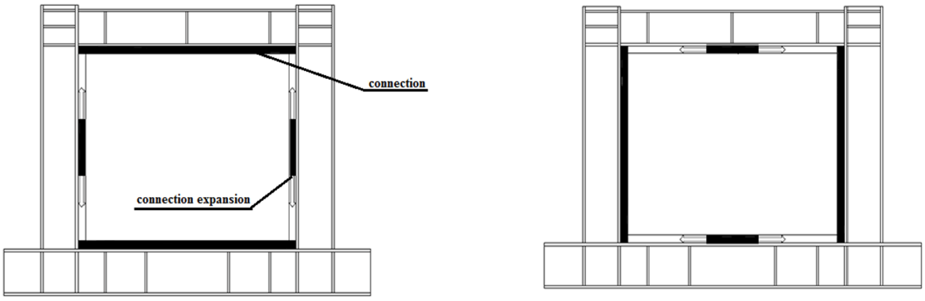


Figure 3: The verification of finite element modeling methodology with laboratory test[2]

3. Model Descriptions

Based on the boundary elements, infill plate conditions, and various infill plate interconnection types with the perimeter frame, 21 computational FE models are established for further studies. The geometry of each model is compatible with the first verified laboratory test established in Figure 2, and the connection types are schematically shown in Figure 4. The nomenclature of the models shown in Table 1 is based on the infill plate connection type and the infill plate connectivity ratio. For examples, computational model named SPSW-60C indicates infill plate interconnection having connectivity ratio of 60% to columns from centers and full connection to beams. It is noted that the connectivity ratio is considered as the length of interconnection line between the infill plate to the boundary elements over the total length of the panel; Therefore, a full connected conventional steel plate shear wall has 100% connectivity ratio.



a) SPSW-C b) SPSW-B

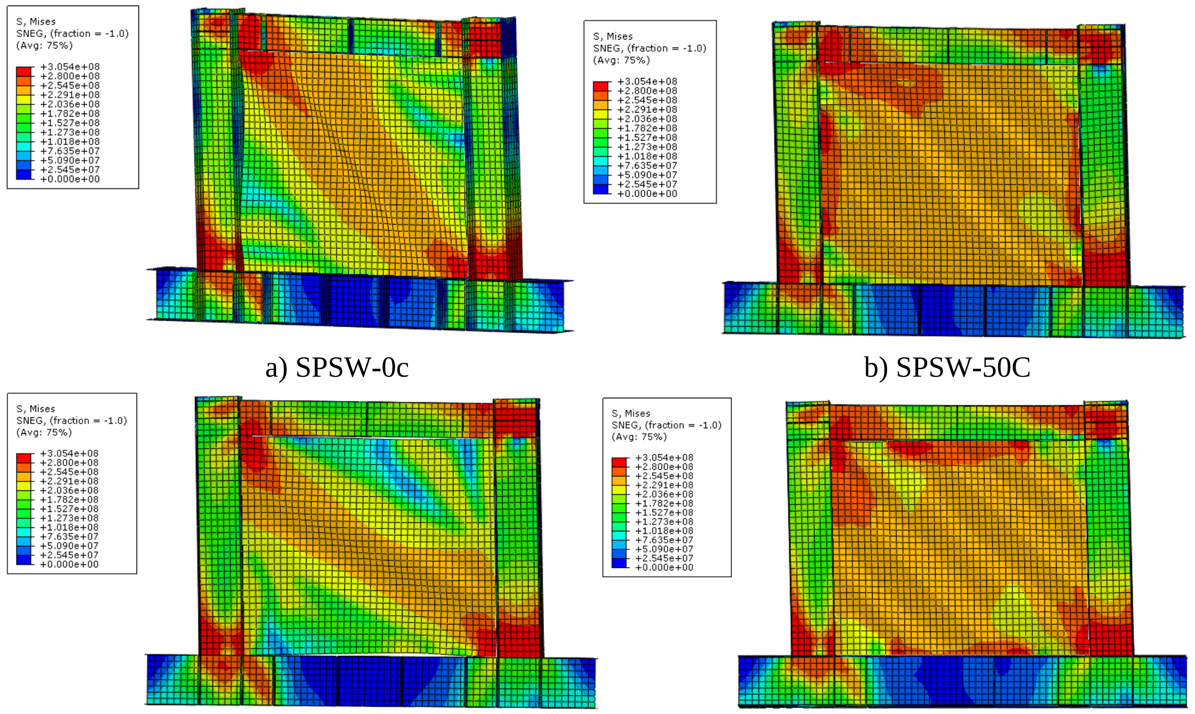
Figure 4: The schematic representation of the infill wall connection conditions for use in steel plate shear wall applications

Table 1: a sample of a table

Models	Infill plate Connection details
SPSW-0C	100% to beams - 0% to columns from center
SPSW-10C	100% to beams - 10% to columns from center
SPSW-20C	100% to beams - 20% to columns from center
SPSW-30C	100% to beams - 30% to columns from center
SPSW-40C	100% to beams - 40% to columns from center
SPSW-50C	100% to beams - 50% to columns from center
SPSW-60C	100% to beams - 60% to columns from center
SPSW-70C	100% to beams - 70% to columns from center
SPSW-80C	100% to beams - 80% to columns from center
SPSW-90C	100% to beams - 90% to columns from center
SPSW-0B	100% to columns - 0% to beams from center
SPSW-10B	100% to columns - 10% to beams from center
SPSW-20B	100% to columns - 20% to beams from center
SPSW-30B	100% to columns - 30% to beams from center
SPSW-40B	100% to columns - 40% to beams from center
SPSW-50B	100% to columns - 50% to beams from center
SPSW-60B	100% to columns - 60% to beams from center
SPSW-70B	100% to columns - 70% to beams from center
SPSW-80B	100% to columns - 80% to beams from center
SPSW-90B	100% to columns - 90% to beams from center
SPSW-F	Connected 100% to all the beams and columns (conventional verified model)

4. Discussion of The Results

The behavior of the steel plate shear walls with different infill plate interconnection are shown in Figure 5. As it is shown the infill plate connection type has a significant effect on the tension field action development and the corresponding diagonal post-buckling folding angles. From the Von-Mises evaluations, it is concluded that the infill plate fully attached to the boundary elements are capable of developing tension field action even in lower drift ratios, while for the SPSWs with infill plate connected to the columns only, the tension field action is partially developed. In addition, those models with infill plate completely or partially attached to all the boundary elements exhibit post-buckling resistance compared to the models attached to one of the boundary elements only.



a) SPSW-0c b) SPSW-50C

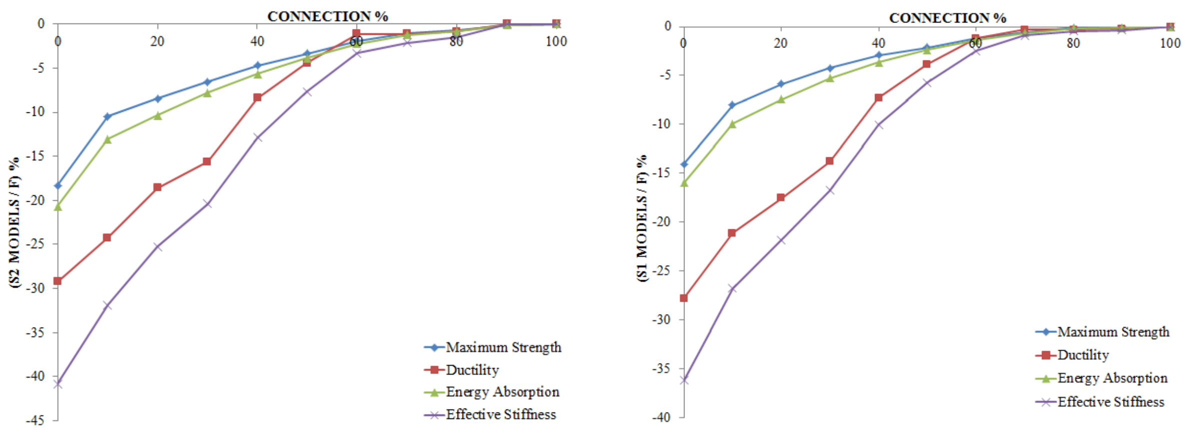
c) SPSW-0B d) SPSW-50B

Figure 5: Von-Mises stress evaluations of the steel plate shear walls with various infill interconnection types at 3% drift ratio

5. Comparison of The Infill plate connections

By increasing the connectivity area of the infill plate in beam-connected models, the significant effect of the columns is observed. Figure 6 shows the effects of the two infill plate connection types with various connectivity ratios on the structural performance of SPSWs. It is shown that the ultimate strength, ductility, energy dissipation and effective stiffness for SPSW's with beam connected infill plates compared to conventional systems are decreased 14.04%, 27.82%, 15.96%, and 36.17%, respectively. Based on the results shown in Figure 6.b, column-only-connected models do not have desirable structural performance compared to other system types due to the partial development of tension field action. It is shown that for the mentioned computational models, the ultimate strength, ductility, energy dissipation and effective stiffness are decreased by 18.33%, 29.21%, 20.63%, and 40.48%, respectively.
Comparing different infill connection types, it is noted that the full beam connected with expansion on columns exhibits a desirable structural behavior compared to the other type of connection. Figure 6.a, and Figure 6.b show that the development of the incomplete tension

field action could significantly reduce the structural performance efficiency, whereas the systems only connected to one of the boundary elements and with the same connectivity ratios have less reduction in overall lateral load resisting behavior. In addition, decreasing the connectivity ratio by 50% results in 6.68%, 2.72%, 4.11%, and 3.13% loss of the initial stiffness, ultimate strength, ductility and energy dissipation in average regardless of the connectivity type. It is concluded that by any slight increase in connectivity ratio regardless of the connection type, the overall performance of the system significantly increases, specifically in SPSWs with lower connectivity ratio values. It is shown that that beside the connectivity ratio of the infill plate, the location at which the connection is established has a significant effect on the performance of the steel plate shear walls.



a) SPSWs fully connected to columns and partially to the beam

b) SPSWs fully connected to the beam and partially to columns

Figure 6: Investigation of the infill plate connectivity ratio on the structural performance of SPSW systems

6. Conclusions

The effect of the infill plate connection with boundary elements on the structural performance of steel plate shear walls is investigated in this study. More than 21 computational models are established after the computational modeling methodology is verified. The structural performance of the four different commonly used infill plate to boundary elements' connection types are considered with various connectivity ratios. It is shown that column-only connected infill plate shear wall reduces the structural loading resisting capacity tangibly more than beam-only due to the limited tension field action development. It is shown that for the systems with infill plates only connected to the columns, the tension field action is partially developed; hence, large diagonal forces are generated leading to large demands on the columns. Systems with partial infill plate connection and connectivity ratio of 80% or more generally have similar structural performance compared to conventional systems with full connected infill plates, which could be implemented as desirable lateral resisting systems with capability of developing plastic hinges far from the beam-to-column connections.

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