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The effect of concrete panel thickness upon composite steel plate shear walls

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ABSTRACT

In this study, the analytical study of concrete stiffened steel plate shear wall (CSPSW) with a reinforced concrete panel on one side and with gap between the concrete panel and steel frame is conducted. CSPSWs have a variety of infill steel plate and reinforced concrete panel thicknesses. The results show that the behavior of CSPSWs and corresponding steel plate shear walls (SPSWs) is utterly disparate. The infill steel plate of SPSW resists lateral load by development of tension fields, as the infill steel plate initiates elastic buckling. However, in CSPSW, the elastic buckling of the infill steel plate is prevented by the introduction of the reinforced concrete panel; hence, the infill steel plate carries out lateral load by pure shear yield. Moreover, during the lateral load, CSPSW undergoes four stages: initial elastic stiffness, shear yield stiffness, post-shear yielding stiffness, and pre-failure stiffness.
The reinforced concrete panel thickness has a remarkable and direct influence upon the shear capacity and the ultimate strength of the CSPSW; furthermore, it is dependent upon the thickness of infill steel plate. Increasing the concrete panel thickness up to a specific value, the shear capacity and the ultimate strength enhance; however, while increasing it beyond that, the shear capacity and the ultimate shear strength of CSPSW remain constant. CSPSW provides a higher initial elastic stiffness, greater shear capacity, and higher ultimate strength as compared to its corresponding SPSW. The ductility ratio and energy absorption of CSPSW is improved owing to introduction of reinforced concrete panel as well.

1. Introduction

Composite steel plate shear wall (CSPSW) consists of an infill steel plate and a reinforced concrete panel on one side or both sides of the infill steel plate. The composite behavior of the system—interaction between infill steel plate and reinforced concrete plate—is ensured by utilizing mechanical connectors such as shear studs or bolts [1]. The huge advantage of CSPSW is that the buckling of the infill steel plate—which is a serious disadvantage of steel plate shear wall (SPSW)—is prevented. To put it simple, as the infill steel plate of SPSW buckles in compression field, considerable reductions in shear capacity, stiffness, and energy absorption are observed. Hence, CSPSWs can be considered an alternative lateral resistance system in steel structures, which is typically utilized as an effective lateral-load resisting system in high-rise buildings, where the story shear loads are markedly large [2].

In the AISC Seismic Provisions, these systems are denoted as "Concrete stiffened Steel Shear Walls." It is worth mentioning that limited research has been carried out on the CSPSWs in which the reinforced concrete panel is attached to one side [3]; hence, this field of study demands more research; especially analytical studies are required to perceive the key parameters for seismic design [4].

The behavior of CSPSW with the reinforced concrete panel on one side is identical with a stiffened steel plate shear wall in which reinforced concrete panel plays a pivotal role in preventing early global and local elastic buckling of infill steel plate. The concrete panel resolves the weakness of infill steel plate in the compression field; as a result, the full pure shear yielding will occur, which is noticeably higher than diagonal tension field yield in steel plate shear wall. In comparison with SPSW, the CSPSW has a smaller infill steel plate thickness; on the contrary, it has a proper ductile manner, greater lateral stiffness, and significant shear strength [1]. Furthermore, since the composite system provides higher lateral stiffness, P–Δ effects and story drift are reduced, which improves performance of steel structures exposed to the devastating earthquake load [2].

The first experimental study of innovative CSPSW by the reinforced concrete panel on one side and with a gap between the reinforced concrete panel and steel frame members—beams and columns—was conducted in 2004 by Zhao and Astaneh-Asl. Two half-scale one-bay three-story specimens, with and without a gap, innovative and traditional, were tested. Cyclic test information depicts that CSPSW can resist lateral forces up to a drift of 0.05 before the shear strength decreases below maximum shear capacity. In addition, the CSPSW with the gap

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shows a very ductile manner, and damage of reinforced concrete panel is less in comparison to the CSPSW without the gap [2]. In 2008, Rahaei et al. carried out experimental and analytical studies on CSPSWs which show that the distance between bolts affect the behavior of the system. Increasing the distance between studs up to a specific point—the distance of 750 mm for a 3 mm infill steel plate—improves both ductility ratio and energy dissipation; and beyond that no change occurs. Furthermore, increasing the distance reduces the slope of load–displacement curve [5]. Arabzadeh et al., in 2010, conducted experimental studies on one-story and three-story CSPSWs with the scale of 1:4 and 1:3 respectively. The results show that by increasing the number of shear connectors, bolts, the shear strength improves, while the ductility of the system reduces. Moreover, utilizing high strength concrete reduces the damage of reinforced concrete panel; however, it does not increase shear strength considerably. In multi-story CSPSWs, columns at lower stories demand more flexural stiffness rather than shear stiffness [6]. In 2011, one SPSW and one CSPSW specimen with concrete-filled circular steel tube columns were tested by Lanhui et al. in order to investigate the comparison of SPSWs and CSPSWs. Both specimens were one-bay two-story with scale of 1:3. The results of cyclic experiments indicate that while the drift of system is less than 1/200, the behaviors of both systems are approximately analogous. Beyond that drift, shear strength and energy dissipation of CSPSW increase evidently, and out-of-plane buckling of infill steel plate is precluded owing to the reinforced concrete panel [7].

In accordance with the mentioned research, the complex behavior of CSPSW needs more analytical research. Moreover, there is no specific nonlinear finite element study on the effect of reinforced concrete panel on one side of the infill steel plate upon the overall system's behavior. In this study, a number of SPSW and CSPSW models were analyzed by utilizing finite element methods. The purpose is to investigate the nonlinear behavior of CSPSW and grasp the effect of reinforced concrete panel and infill steel plate thickness upon the CSPSW's behavior.

2. Method of study and validation of results

2.1. Models

In this paper, a number of one-story one-bay SPSW and CSPSW models are taken into account. The models have different infill steel plate thicknesses ($t_w = 4, 5, 6,$ and 7 mm). The CSPSW models have different reinforced concrete panels; furthermore, there is a 75 mm gap between steel boundary elements, beams and columns, and the reinforced concrete panel.

It is considered that both the infill steel plate and reinforced concrete panel resist lateral load corresponding to the full shear yield of infill steel plate; hence, the boundary elements are designed to ensure this principle. Plastic hinges are expected to merely locate at beams or the bottom of columns. The boundary elements are designed in accordance with recommendations in AISC Seismic Provisions which are referred to steel plate shear wall design [3]. The designed sections for beams and columns are W12 × 230 and W12 × 305 respectively, as shown in Fig. 1.

The center to center distance between two bolts is 240 mm which ensure yield of infill steel plate before its local elastic buckling [1]. The details of models are given in Table 1, and a typical model of CSPSW is illustrated in Fig. 1, with L/h = 1, h = 300 mm, and L = 300 mm.

2.2. Numerical modeling

The commercial finite element software, ABAQUS/Explicit, is utilized for push-over analyses of complex behavior of CSPSW [8]. Shell elements (SR4) are selected for the infill steel plate. Solid elements (C3D8R) are chosen for the columns, beams, concrete panel, and washers which are assumed to be the most suitable choices. Three-dimensional beam elements (B31) for bolts and 2-node three-dimensional truss elements (T3D2) for reinforcements are utilized. Fig. 2 shows the typical finite element model of CSPSW.

The bolts connect the reinforced concrete panel to the infill steel plate; therefore, the rotational degrees of freedom for both ends of a bolt are released. This simulation restrains out-of-plane displacements of the reinforced concrete panel and free in-plane rotation of bolts, which is the actual behavior of CSPSW specimen. In addition, the frictionless contact pair algorithm between the infill steel plate and the reinforced concrete panel is stimulated in the models, and the gravity load is not considered for them [5].

In SPSW models, the initial imperfection magnitude, h/10,000, corresponding to the first buckling mode is applied in models to help the development of the tension field [9]; however, applying these imperfections do not have a significant effect on analysis results [10,11]. In the CSPSW models, the initial imperfection is not applied due to introduction of the reinforced concrete panel. In other words, the reinforced concrete panel restrains the infill steel plate and prevents its buckling before it yields [1].

2.3. Material properties

ASTM A572 Gr.50 (Fy = 345 MPa) and ASTM A37 (Fy = 248 MPa) are selected for boundary members and infill steel plate respectively. ASTM A325 (Fy = 600 MPa) is utilized for bolts; moreover, steel material with yield strength of 365 MPa is chosen for reinforcements. The Young's modulus is 200 GPa and the Poisson's ratio is 0.3. The material stress–strain behavior curves are shown in Fig. 3.

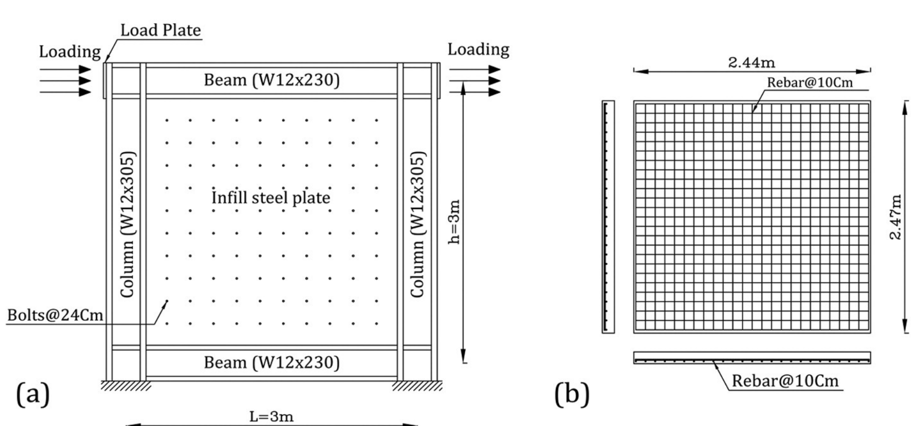

Fig. 1. A typical CSPSW system: (a) Boundary elements and the steel plate. (b) The reinforced concrete panel.