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Cyclic performance of cross restrained steel plate shear walls with transverse braces

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ABSTRACT

This paper presents an investigation on the cyclic performance of cross restrained steel plate shear walls (SPSWs) with transverse braces. Transverse braces connecting to two columns are proposed to replace horizontal cross stiffeners on the infill steel plates. Effects of transverse braces on the performance of SPSWs are estimated through an experimental study and a finite element analysis. Two 1/3-scale two-story single-bay SPSW specimens, including one unstiffened SPSW and one cross restrained SPSW with transverse braces, are first tested under the quasi-static cyclic loading. Subsequently, finite element models for SPSWs are developed and verified by the test results. Cyclic performance of SPSW structures with different restrains for the infill steel plates are compared in terms of failure mode, loading capacity, energy dissipation capacity and stiffness degradation. Emphasis is given on the stress development and out-of-plane deformation of infill steel plates. The results show that use of transverse braces as the substitute of horizontal stiffeners enhances the loading capacity, energy dissipation capacity and ductility of SPSW structure. It is also effective to homogenize stress distribution and to restrain the out-of-plane deformation of infill steel plates, which finally decreases the additional bending moments applied to the columns. Compared with the unstiffened SPSWs, the maximum inward flexural deformation of columns in the cross restrained SPSWs with transverse braces is reduced by about 40.0%. It has demonstrated that the proposed cross restrainers combined with transverse braces are effective in improving the cyclic performance of SPSWs.

1. Introduction

Steel plate shear walls (SPSWs) have been extensively used as lateral load resisting systems in past few decades. They have excellent energy dissipation capacity, superior ductility and inherent redundancy [1–4]. For instance, the 35-story Kobe City Hall Tower built with SPSWs exhibits excellent seismic performance during the 1995 Kobe earthquake. SPSWs are also adopted in 75-story Tianjin Jinta Tower which is the world's tallest steel shear walled building [5]. Habashi and Alinia [6] conducted a numerical study on the interaction between the infill steel plates and the frame members and found that the infill steel plates are effective in resisting horizontal loads at the initial stage of loading. Once the tension field forms in the steel plate, the applied loads are mainly taken by the frame members. Lubell et al. [7] reported that columns with insufficient stiffness are prone to exhibit obvious inward flexural deformation under the tension field action in the steel plates. The occurrence of inward flexural deformation reduces the stresses in the middle of columns and increases the stresses near the ends of columns. This promotes the formation of plastic hinges and the failure of columns in an "hourglass" form, which is therefore named "hourglass effect". Yu et al. [3] and Li et al. [8] confirmed that the premature buckling of the infill steel plate and the premature failure of the frame columns decrease the ultimate loading capacity of the SPSWs. Thus, proper improvements are needed to prevent the premature failure of columns and further enhance the structural performance of SPSWs.

It is well-known that the stiffeners can provide effective out-of-plane restraint and axial support for the infill steel plate, which significantly improves the overall performance of SPSW structure [9]. Sigariyazd et al. [10] reported that the diagonally stiffened SPSW structure has good energy dissipation capacity and proposed a formula for estimating the loading capacity of diagonally stiffened SPSWs. Zhao et al. [11] analysed the stiffness and elastic critical stress of the stiffeners installed in SPSWs and proposed a formula for calculating the critical elastic shear strength of stiffened SPSWs. Chinese standard JGJ/T380 [12]

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specifies the requirements on the rigidity of stiffeners for SPSW. Yang et al. [13] conducted an elastic buckling analysis of the SPSWs stiffened by vertical tubes and correlated the compressive buckling strengths to the rigidities of stiffeners. Alavi and Nateghi [14] performed quasi-static tests on one unstiffened SPSW structure and two diagonally stiffened SPSW structures, and concluded that the stiffeners cannot increase the ultimate shear strength of SPSW structure. Sabouri-Ghomi and Mamazizi [15] carried out an experimental investigation on the stiffened SPSWs with two rectangular openings. Stiffeners were installed around the openings. Test results showed that the ultimate loading capacity, stiffness and energy dissipation are almost the same for the SPSWs regardless of the openings in steel plates. Guo et al. [16] investigated the influence of connecting form and arrangement of stiffeners on the seismic performance of SPSW structure. The study revealed that the cross stiffeners dividing the infill plate into small cell plates are effective in reducing the height-to-thickness ratio and delaying the buckling of the thin steel plate, which in turns to improve the loading capacity and stiffness of the infill steel plates. However, stiffeners installed through direct welding cause initial defects to the infill steel plates due to residual stress and welding distortion, which necessitates the development of new buckling restraining system for the infill steel plates in SPSWs.

To overcome the defects of the conventional welding stiffeners, several buckling restraining methods for infill steel plate of SPSW structure have been developed. For instance, precast concrete cover panels have been adopted to restrain the infill steel plates in SPSWs. This is a typical non-welded buckling-restrained SPSW (BR-SPSW) structure as concrete panels are connected with the infill steel plate by the bolts. Jin et al. [17] studied the seismic performance of precast concrete panel-restrained SPSWs structure with inclined slots on the infill steel plates, and found that the slotted infill steel plate can avoid transferring excessive forces to the boundary frame elements. Liu et al. [18] investigated the structural behaviour of BR-SPSWs with various height-to-width ratios for the steel plate, and proposed the simplified formulas to predict the yielding capacity of the BR-SPSWs with infill steel plates connected with beams only. Wei et al. [19] proposed a novel partially connected BR-SPSW, in which four corners of infill steel plates were bolted to the boundary frame elements by steel angles and gusset plates. A modified calculation method for shear strength of the partially connected BR-SPSW was also developed. In addition, Li et al. [8] and Tsai et al. [20] proposed a new restrained SPSW structure, which adopted pairs of the transverse braces sandwiching over both sides of the infill steel panels and connecting to the boundary columns. A design method for this SPSW structure was introduced and validated by quasi-static tests of two full-scale two-story narrow SPSWs. It was found that transverse braces can provide efficient horizontal support for the frame columns so that the horizontal forces in both columns can be alleviated. As a result, the inward flexural deformation of columns due to the tension field in steel plates can be prevented. Moreover, the use of the transverse braces in the narrow SPSWs increases the angle of tension field in relative to vertical line to be around 45°, which is beneficial to increase shear deformation of the steel plates. However, there is lack of sufficient investigation on the cyclic performance of restrained SPSWs, particularly for those with wide steel plates.

To overcome the limitations of welded stiffeners and to address the research needs on wide SPSWs with transverse braces, the cross restrainers combined with transverse braces are proposed to replace conventional stiffeners, and subsequently improve the cyclic performance of SPSW structure. An experimental study of two 1/3-scale two-story single-bay SPSW structure and a finite element analysis of three SPSW structure with different restraining configurations are conducted. Experimental results of SPSW structures in terms of failure mode, hysteretic behaviour and connection performance are presented. Following the validation of finite element models for SPSW structure, loading capacity, energy dissipation, stiffness degradation and infill-plate deformation of SPSW structure are further discussed.

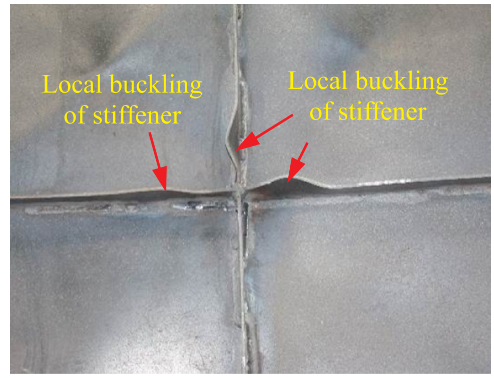

Fig. 1. Local buckling of welded stiffeners on infill steel plate.

2. Cross restrained SPSWs with transverse braces

2.1. Development of non-welded cross restrained SPSW with transverse braces

In the conventional stiffened SPSW structures, stiffeners are normally installed on the infill steel plates through direct welding, which may cause high residual stress and large welding distortion in the steel plates and stiffeners. As seen in Fig. 1, welded stiffeners are prone to fail in the form of local buckling prior to the overall failure of the SPSWs, which weakens the buckling resistance for the infill steel plates. Thus, innovative non-welded cross restrainers are proposed as the replacement of the welded stiffeners in SPSWs to overcome the premature buckling of stiffeners installed on infill steel plates. Fig. 2 shows a schematic view of the proposed non-welded cross restrained SPSWs with transverse braces. The non-welded cross restrainers are installed on the both sides of the infill steel plate by the threaded bolts passing through the reserved holes and steel plate. The horizontal restrainer is connected to the columns while the vertical restrainer is disconnected with the beams. Thus, the proposed restrainers can restraint the out-of-plane buckling of infill steel plates as well as serve as the support for the frame columns.

In the restrained SPSW structures [8], transverse braces connecting to the columns tend to restrain the out-of-plane buckling of the infill steel plate, which in turns to significantly contribute to horizontal resistance of the whole frame. As a result, the force demands from the frame columns can be properly reduced. The transverse braces can also divide the infill steel plate into several parts, which is suitable for the narrow SPSWs through reducing the width-to-height ratio of infill steel plates. It means that transverse braces are not applicable to the SPSWs with a high width-to-height ratio of the infill steel plates. It is recommended to install vertical restrainers for the SPSWs with a high width-to-height ratio of the infill steel plate.

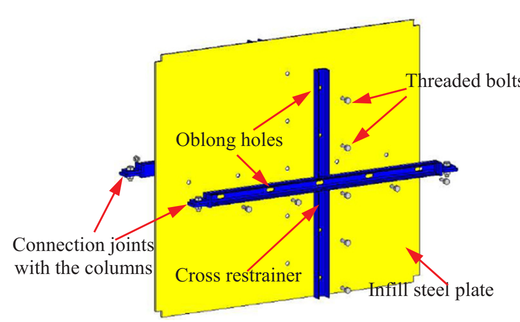

Fig. 2. Schematic view of non-welded cross restrainers combined with transverse braces.