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Effects of non-welded multi-rib stiffeners on the performance of steel plate shear walls

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ABSTRACT

This paper presents a numerical investigation of the dynamic performance of steel plate shear walls (SPSWs) stiffened by non-welded multi-rib stiffeners. Multi-rib stiffeners are installed on both sides of the steel plate and connected by threaded bolts through the plate, rather than direct welding as conventionally being done. The influence of constraints between multi-rib stiffeners and steel plate on the performance of SPSWs is first examined by finite element analysis. Afterwards, a numerical model for SPSW structure is developed and validated by the test results. The dynamic performance of SPSW structures with and without non-welded stiffeners is compared in terms of inter-story drift, acceleration response and out-of-plane deformation. Test results indicate that constraints between multi-rib stiffeners and steel plate slightly affect the loading capacity of SPSWs. The loading capacity of the SPSWs with non-welded multi-rib stiffeners is 5.8% lower than that with welded stiffeners. However, buckling of stiffeners can be avoided in the non-welded multi-rib stiffened SPSWs. For the dynamic performance of SPSW structures, use of non-welded multi-rib stiffeners is effective in reducing the inter-story drift, acceleration and out-of-plane deformation of SPSW structures under earthquake attacks, particularly for those subjected to main shocks followed with aftershocks. The use of non-welded stiffeners decreases the maximum inter-story drift and the maximum out-of-plane deformation of SPSW structures by 14.7% and 57.0%, respectively. In addition, non-welded multi-rib stiffeners can uniformly distribute the stiffness of SPSWs along the floors. In general, the proposed non-welded multi-rib stiffeners are effective in enhancing the dynamic performance of SPSWs.

1. Introduction

Steel plate shear walls (SPSWs) have been recognized as excellent seismic-resistant structural systems with stable hysteretic behavior and good energy dissipation capacity [1]. However, SPSWs are prone to buckle even at the elastic stage of loading, and the out-of-plane deformation of steel plates (also known as "breathing" effect) causes loud banging sounds and tremors to the occupants. Increasing the thickness of steel plates is one of solutions adopted to enhance its buckling resistance, nonetheless, buckling of infilled steel plates still occurs when the structure is subjected to a moderate or strong earthquake [1–4]. In addition, steel plates are allowed to buckle in shear and subsequently contribute to resist horizontal force through diagonal tension fields. This will probably reduce the stability of columns due to the additional moments introduced by diagonal tension fields. As a result, plastic hinges tend to form at the ends of columns, followed with a "hourglass" phenomenon on the columns [3]. To tackle this problem in the literature, various types of stiffened SPSWs and composite SPSWs have been proposed to enhance the buckling resistance of the infilled steel plates.

Sigariyazd et al. [5] investigated the behavior of SPSWs with diagonal stiffeners in various configurations. Experimental and numerical results from their study indicated that SPSWs with diagonal stiffeners possess excellent energy dissipation capacity. Alavi and Nateghi [6] carried out a quasi-static test on SPSWs with and without diagonal stiffeners. It was found that the addition of stiffeners is effective in enhancing the lateral loads of steel plates. Alinia and Shirazi [7] examined the influence of the configuration of stiffeners on the performance of SPSWs, and highlighted that unidirectional stiffeners are more effective in resisting buckling than bidirectional ones. Yu et al. [8] reported that SPSWs with added stiffeners exhibit enhanced cyclic behavior based on an experimental investigation. The steel plates mainly contribute to enhancing the stiffness and the buckling resistance of the structure at the initial stage of loading, while the stiffeners improve the force distribution among steel plates in the structure. Guo et al. [9] investigated the performance of SPSWs with semi-rigid beam-column connections and cross stiffeners on steel plates. It illustrated that the cross stiffeners are effective in enhancing the buckling resistance and loading capacity of SPSWs. This was achieved by decreasing the

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height-thickness ratio of steel plates with the incorporation of cross stiffeners. In summary, installation of stiffeners on steel plates is one of the effective methods to improve the overall structural performance of SPSWs.

Alternatively, Guo et al. [10] studied the performance of SPSWs with adding reinforced concrete covers on infilled steel plates. It was reported that the concrete covers are prone to separate from the steel plates due to their poor bonding, and have the drawback of being heavy. Wei et al. [11] proposed a novel partially connected buckling-restrained SPSW and illustrated its shear mechanism based on finite element analysis. Jin et al. [12] conducted a numerical study on buckling-restrained SPSWs with inclined slots. It was found that the width of steel strips and width-to-thickness ratio of steel panels are the main parameters affecting the performance of SPSWs. With the contribution by stiffeners, SPSWs with inclined slots exhibit ductile behavior. Currently, most stiffeners are installed on steel plates through direct welding, which causes initial defects, such as large residual stress and welding distortion. For instance, residual stress caused by stiffener welding in SPSWs was approximated to be 100 MPa [13]. Besides, welded stiffeners subjected to lateral loading often fail in local buckling prior to the overall failure of the SPSWs as shown in Fig. 1 [8], which inhibits the buckling resistance of stiffeners for SPSWs.

To overcome local buckling of stiffeners installed on steel plates, the authors developed non-welded multi-rib stiffeners as a replacement for welded stiffeners for SPSWs [14]. The non-welded stiffeners are attached on the steel plates and connected by threaded bolts through steel plates. In comparison with traditional welded stiffeners, non-welded stiffeners can avoid large residual stress and welding distortion in structural members. As the non-welded stiffeners will neither be involved in the lateral resistance of the structure nor serve as anchoring ends of the steel plates, they are mainly subjected to the normal force perpendicular to the steel plates. This can effectively avoid the local buckling of stiffeners before the yielding of steel plates. In addition, non-welded multi-rib stiffeners are suitable for on-site installation resulting in the reduction of welding operations. In general, the use of non-welded multi-rib stiffeners can provide buckling resistance for steel plates as well as eliminate the limitations of welded stiffeners. However, there are limited studies focusing on the performance of SPSWs with non-welded stiffeners. The influence of constraints between non-welded multi-rib stiffeners and steel plates on the performance of SPSWs still needs further study.

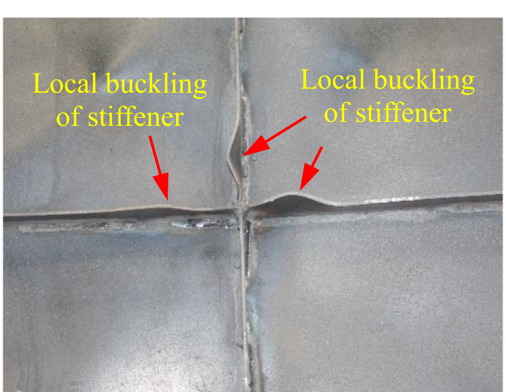
The seismic performance of SPSW structures has been widely studied in the past decades [5–9], although few investigations concentrated on dynamic analysis of SPSW structures. Rezai et al. [15] conducted a shaking table test on a 1/4-scale semi-rigid frame with unstiffened steel plate walls, and their test results indicated that the occurrence of tension belts on steel plates weakens the overall performance of SPSW structures. Ge et al. [16] experimentally investigated the dynamic performance of buckling-restrained SPSW structures. It was reported that the buckling-restrained SPSWs exhibited satisfactory seismic performance under large seismic excitations. Moreover, most studies on the dynamic behavior of SPSWs was performed under a single ground motion or a main earthquake. Statistical studies have demonstrated that strong aftershocks occur after a main shock [17]. The aftershocks have the characteristics of high frequency, intensity and wide distribution, and can also cause serious damage to structures. Therefore, it is interesting to investigate the dynamic response of stiffened SPSW structures subjected to aftershocks, particularly for those with newly proposed non-welded multi-rib stiffeners.

In this study, the influence of constraints between stiffeners and steel plates on the structural performance of SPSWs was first investigated. Afterwards, a nonlinear finite element analysis of SPSW structures was developed and verified by a shaking table test. The dynamic performance of SPSW structures with and without non-welded stiffeners was compared in terms of maximum inter-story displacement, acceleration response and out-of-plane deformation under strong earthquakes with and without aftershocks. The focus was on the stiffening effect of the proposed non-welded multi-rib stiffeners for SPSW structures.

2. SPSWs with non-welded multi-rib stiffeners

Fig. 2 shows the assembly process of the non-welded multi-rib stiffeners for SPSWs. The multi-rib stiffeners consist of transverse and longitudinal steel belts as shown in Fig. 2(a). Grooves are cut on the steel belts at the intersection of ribs in both directions. The transverse and longitudinal steel bels are mutually embedded to form multi-rib grid as shown in Fig. 2(b). Subsequently, the circular tubes are welded to the multi-rib grid at the intersection of the ribs. The length of tube is identical to the width of the ribs. It is worth noting that the welding has no impact on the steel plates. Two layers of multi-rib stiffeners are attached to both sides of the steel plate and are connected by threaded bolts passing through the welded tubes and steel plates as shown in Fig. 2(c). A pair of bearing plates is also provided for connecting the stiffeners. Finally, the steel plates with non-welded multi-rib stiffeners are bolted to the frame through the welding bracket plates. As seen in Fig. 2(d), the non-welded multi-rib stiffeners are disconnected from the frames. As compared with traditional welded stiffeners, the proposed non-welded multi-rib stiffeners are much easier to replace and install.

Two types of non-welded stiffeners, including fixed and sliding multiple ribs, are proposed according to the constraints between stiffeners and steel plates, and are designed with different gap sizes between the tubes and the threaded bolts. For the fixed multi-rib stiffeners, the inner diameter of tube is properly fit with the diameter of threaded



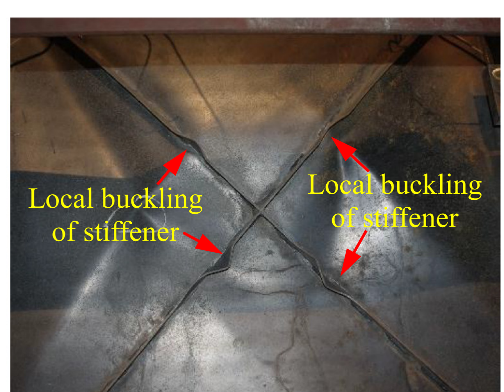


Fig. 1. Local buckling of stiffeners on steel plates.