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Introduction of stiffened large rectangular openings in steel plate shear walls

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ABSTRACT

The nonlinear behavior of steel plate shear walls (SPSWs) with stiffened large rectangular openings used as windows or doors in buildings is studied. A number of SPSWs with and without openings are numerically analyzed, and the results are utilized (a) to characterize the behavior of SPSWs with the openings, (b) to study the effects of various opening features as well as size of local boundary elements (LBE) around the opening and thickness of infill plates on either side of the opening and (c) to investigate the changes in the system strength, stiffness and ductility due to the introduction of the openings. Results show that the procedure addressed by AISC Design Guide 20 for design of beams above and below the opening level is not perfect. Use of thicker or thinner infill plates or weaker profiles for the LBE can alter the yielding sequence in the system. Notably, the type, location and geometry of stiffened openings are not influential themselves on the system strength, although different LBE sizes required for different openings may have some effects. The introduction of stiffened openings in different SPSWs increases both the ultimate strength and stiffness, while somewhat decreases the ductility ratio.

1. Introduction

Steel plate shear walls (SPSWs) have been increasingly utilized as a lateral force resisting system, which resist both earthquake and wind forces. This structural system has been used in significant buildings beginning decades ago, and implementation has accelerated since the recent years [1]. They provide an effective and economical solution for new construction as well as retrofitting of existing structures. A conventional SPSW consists of thin stiffened or unstiffened steel plates surrounded by horizontal and vertical boundary elements (HBE and VBE) that can be multiple stories high and one or more bays wide.

Early designs of SPSWs were based on the concept of preventing shear buckling in the infill plate by using either thick infill plate or by adding stiffeners to the infill plate, but in recent years, the idea of utilizing the post-buckling strength with the use of thin unstiffened infill plate has gained wide acceptance from researchers and designers globally. Typical SPSW has slender infill plates that are capable of resisting large tension forces by developing diagonal tension fields in the infill plate, but little or no compression. They should be expected to buckle under very small lateral loads or even considered pre-buckled under their own weight prior to loading. It is known that plastic deformations in SPSWs should primarily be provided by the infill plates [1,2] and that the boundary members should be designed so as to develop the full tension strength of the infill panels.

Numerous research programs and large-scale experiments have been shown that this system possesses high level of initial stiffness, strength, ductility and robustness under cyclic loading [3–12]. SPSWs offer significant advantages over many other lateral load-resisting systems in terms of foundation cost, saving steel, performance, ease of design, speed and simplicity of construction and usable space in buildings [1,13]. They can also be accommodated to allow different types of openings within their infill plates.

To date, experimental and analytical research on thin unstiffened SPSWs is mainly focused on the behavior of SPSWs with solid infill plates (i.e. without openings) and thus, limited research on various types of openings in SPSWs or shear panels has been performed.

Roberts and Sabouri-Ghomi [14] conducted a series of quasi-static cyclic loading tests on unstiffened steel plate shear panels with centrally placed circular openings. Based on the test results, the researchers recommended that the strength and stiffness of a perforated panel can be conservatively approximated by applying a linear reduction factor to the strength and stiffness of a similar solid panel. Deylami and Daftari [15] analyzed more than 50 models with a rectangular opening in the center of the panel using finite element method to investigate the effects of some important geometric parameters, such as plate thickness, the opening height to width ratio, and the areal percentage of the opening. The opening had only two stiffeners with limited length on its vertical edges which were not continued across the height of the panel. They concluded that the introduction of the opening, even at relatively small percentage, caused an important decrease of shear capacity. In thinner steel plate shear

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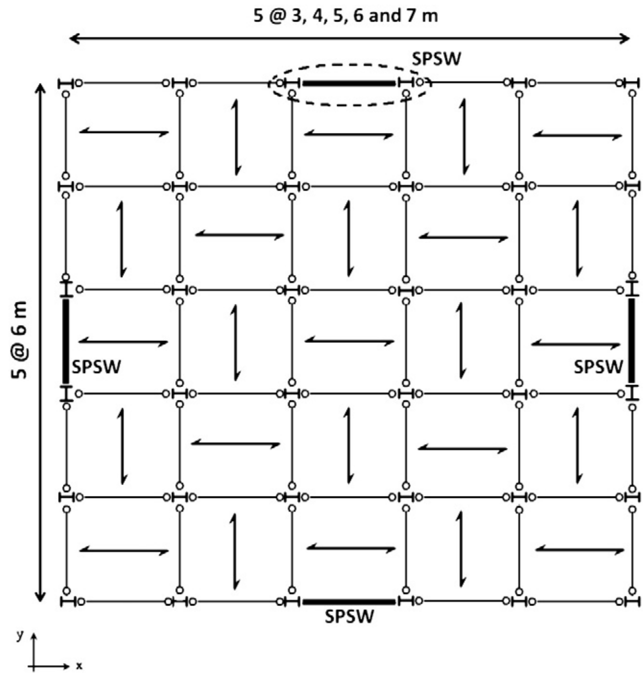

Fig. 1. Typical plan and considered SPSW.

walls, the maximum shear capacity has been achieved by a smaller ratio of height to width of the opening. Also, the decrease in shear capacity after reaching a maximum amount has been slower in thick plates than in thin plates. Hitaka and Matsui [16] experimentally studied the behavior of 42 one-third scale steel shear wall specimens with vertical slits under static monotonic and cyclic lateral loading. The test data indicated that, when properly detailed and fabricated to avoid premature failure due to tearing or out-of-plane buckling, the wall panels responded in a ductile manner. Vian [17] conducted experimental works on a pattern of multiple regularly spaced circular perforations in the infill plate and a reinforced quarter-circle cut-outs in the upper corners of the infill plate, and Purba [18] proposed an equation to determine the shear strength of a perforated infill plate with the specific perforation pattern proposed by Vian [17]. Alinia et al. [19–21] performed a series of finite element analyses to investigate the influence of central and near border cracks on buckling and post-buckling behavior of shear panels. It is implied from the results of this research that, anyhow, discontinuity in tension zones can have significant influence on buckling and post-buckling behavior of shear panels. The ultimate strength of perforated steel plates under shear loading was studied by Paik [22], and the linear and nonlinear behavior of steel shear panels with circular and rectangular holes by Pellegrino et al. [23]. Valizadeh et al. [24] experimentally investigated cyclic behavior of perforated steel plate shear walls with a circular opening at the center of the panel. The obtained results showed that the creation of openings reduced the initial stiffness and strength and noticeably decreased the energy absorption of the system.

Openings are often required in SPSWs for functional reasons. One of the most usual types is the large rectangular openings utilized as doors or windows to allow entry to stairs and elevators or provide outside view and light, respectively. These happen frequently when SPSWs are used in the building cores or as the facade panels. The design procedure is similar to the typical design of SPSW. In the case of such large openings, use of horizontal and vertical local boundary elements (LBE) around the opening to anchor and transmit the infill plate tension forces to the surrounding boundary members (i.e. HBE and VBE) at their ends is inevitable. Moreover, to compensate the infill plate total area reduction at the opening level, the thickness of infill panels on either side of the opening must be increased. As such, where the resulted panels are often of slender proportions, providing the same total area of the original infill will thus be adequate. However, infill plates immediately above and below the opening are the same thickness as would be provided if there were no opening. The introduction of openings and LBE does not require redesign of VBE in SPSW, especially where the openings are not repeated at every level, and the VBE size will be in turn dictated by the demands at other levels. HBE above and below the opening must be redesigned, however, due to the local overturning demands at the opening. General treatment of the design of stiffened rectangular openings in SPSWs was provided by AISC Design Guide 20 [1].

According to the author's knowledge and the literature review, there is no specific work available for explaining various aspects of the nonlinear behavior of SPSWs with stiffened large rectangular openings, and the amount and quality of changes in the system behavior due to the introduction of such openings have never been studied.

In the present study, a number of SPSW models with and without openings are numerically analyzed using the finite element method. Primary concern is paid to window-type openings. The effect of opening type, however, is considered separately by comparing the behavior of typical single-storey SPSWs with window and door-type

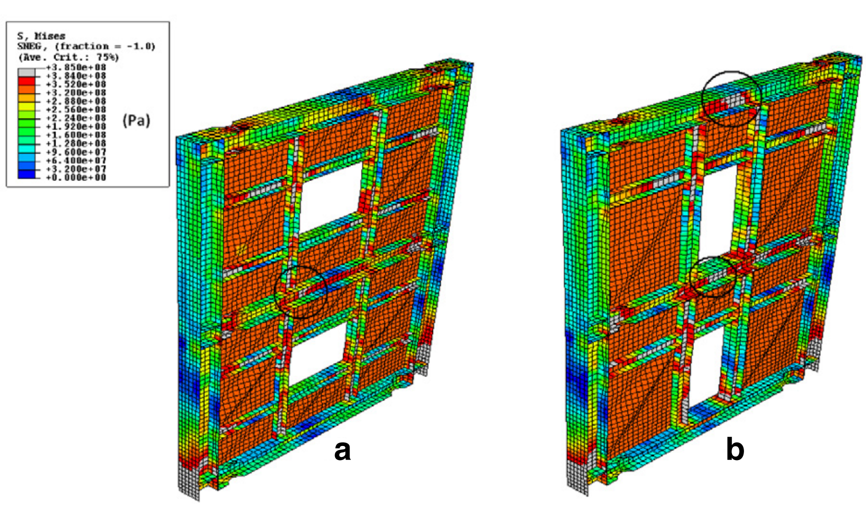

Fig. 2. Shear yielding occurrence in the central part of some beam webs in preliminary SPSW models with openings designed according to AISC 820: (a) a two-storey SPSW with window-type openings, and (b) a two-storey SPSW with door-type openings.