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Seismic behavior of steel plate shear wall with reduced boundary beam section

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ABSTRACT

In this paper a steel plate shear walls (SPSWs) with specific type of reduced beam section is proposed. The perimeter framing configuration around the steel plate shear wall plays an important role in the ductility of system. In order to prevent brittle failure of beam-column connection, the beam section is weakened with different methods. The methods included the reduction of the beam section with circular and elliptical web openings, vertical slots in the web and also the reduction of the beam flange. The nonlinear finite element analysis results showed that the model with slots in the beam web has the best performance in terms of ductility, energy absorption, stiffness and shear strength than the other proposed models. Parametric study is carried on the geometry of the slots and some design limitations proposed on the size and location of slots, based on the analysis results. The analysis results on different models showed that the slotted beam models could reach to an average story drift of 4%, which is a high value for a steel shear wall system. The results showed that most effective parameter is the length of slotted region. The use of proposed slotted beam model in shear walls with different story height to length ratios are studied, and concluded that decreasing the height to length ratio of the wall results in decrease of ductility. Push-over analysis is also carried on a four-story steel plate shear wall system with and without slots in the beam. Results showed that in the slotted beam model the plastic strain can be fully distributed among the steel plate shear wall and the slotted part of the beam web, the connections remaining elastic, at 4% story drift.

1. Introduction

Steel plate shear walls (SPSWs) are known to be an effective system for resisting seismic forces. A properly designed SPSW has high elastic stiffness, stable hysteretic behavior, high energy dissipation capacity and ductility, It is an economic and efficient lateral force resisting structural system in tall buildings [1,2]. The steel plate can be welded or bolted to the boundary frame. The shear buckling of thin steel plate usually governed the ultimate strength of the steel plate shear wall. In SPSWs with stiffener, the stiffeners prevent the plate buckling, and as a result the strength of steel plate goes up. In North America, the thin unstiffened steel plates are commonly used for the infill plates, relying on post-buckling strength of the infill plates to calculate the capacity of SPSWs [1].

In the past two decades, several experimental studies have been carried out on the thin steel plate shear walls by Caccese et al. [6], Driver et al. [7] and Lubell et al. [8]. Thorburn et al. [3] and Timler et al. [4] presented a strip model for the analysis of thin steel plate shear walls. Hitaka and Matsui [9] studied the performances of slit in steel shear walls. Robert and Sabouri-Ghomi [10–12] introduced the plate-frame interaction theory for predicting the linear and nonlinear behavior of different steel plate shear walls. The effect of holes in the infill plate on unstiffened SPSWs were investigated by Vian Bruneau [13]. Nateghi and Alavi [14,15] evaluated the seismic performance of a diagonally stiffened steel shear wall with a central opening in comparison with an unstiffened and diagonally stiffened solid plate shear walls, Design rules of the thin steel plate shear wall are also specified in the design specification, such as AISC [16] and CSA [17].

Thorburn et al. [3], Timler and Kulak [4], and Tromposch and Kulak [5] firstly found that the unstiffened thin steel plate walls had high post-buckling strength with good ductility behavior. Early buckling of thin steel plate shear wall occurs under lateral force, and the structure still has high potential of load-carrying capacity after buckling, which is caused by “tension fields” of infill plate. In fact in the case of unstiffened steel plate, load transfer mechanism comprises the contribution of boundary frame moment resisting action and infill plate diagonal tensile field. The surrounding framing members are generally “capacity designed”, i.e., designed to develop the in-fill plate tension

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field capacity, while themselves remaining essentially elastic.

In recent years, some researchers were interested in studying SPSW system because its dual characteristics regarding the frame and infill wall action which may be well treated as two sub systems, the shear capacity of an infill wall is affected by the rigidity of its surrounding frame members [18]. With regard to the interaction effect between the infill plates and frame members Alinia and Dastfan [19,20] analyzed the nonlinear response of SPSW dual systems under lateral loading.

In this paper, some models of unstiffened SPSWs with weakened beam section, have been proposed to prevent brittle failure of beam-column connection. The methods included the reduction of the beam section with circular and elliptical web openings, vertical slots in the web and also the reduction of the beam flange.

2. Numerical analysis

2.1. Description of theoretical model

This research herein is based on finite element non-linear static analysis using ANSYS (Version 15.0) software [20]. The numerical model uses finite strain iso-parametric shell element, SHELL 181, built in ANSYS element library [20]. All members, including webs and flanges of beams and columns, and the infill plate were modeled with SHELL 181 elements. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a four-nodded element with six degrees of freedom at each node. Geometric nonlinearity (large deformation) is included in the analysis. In order to capture the diagonal buckling of the steel shear wall, initial modal analysis is carried on. Then an initial imperfection is applied on the steel shear wall, based on captured modal shapes. Multi-linear post yield stress-strain curve is defined for the steel material. It is assumed that shear walls has lateral support at the roof level and the models are restrained at the beam-column intersection nodes against out-of-plane translation.

The analysis conducted herein was essentially non-linear static analysis at which loading was applied as lateral displacement, i.e. displacement controlled, to enhance convergence of numerical solution. The converged solution after each displacement increment was obtained by iteration using the Full Newton-Raphson technique [20]. Push-over loading was conducted by applying a gradually increasing nodal displacement in one direction, from left to right, at the level of top beam whereas cyclic loading was applied according to the loading protocol of FEMA [21] at which the model was subjected to loading cycles with progressively increasing displacement magnitude. Due to the high non-linear nature of the problem, severe convergence difficulties occurred due to sudden increase in the out-of-plane displacements of in-fill plate. Therefore a special nonlinear stabilization technique was adapted by adding an artificial damper at each node [20]. The force in the damper was proportional to nodal displacement per increment. Therefore the node that tended to be unstable had large displacement increment causing large damping force that reduced the displacement and stabilized the model. On the other hand, the effect of damping forces was minimal at stable nodes with small displacement increment [20].

2.2. Verification of numerical results

The finite element results are compared with the sample test results of driver's four-story frame test [7]. According to the experiment, loading was applied as lateral force. The loading and geometry details of experimental model can be seen in Fig. 1.a. The finite element model is shown in Fig. 1.b.

Load-displacement curves obtained from the finite element model has been compared with the experimental results of driver's four-story frame test [7]. The results, as depicted in Fig. 2, show good agreement.

3. Proposed model

Since the steel shear walls have negligible compression strength, shear buckling occurs at low levels of loading and it is assumed that lateral resistance is provided by diagonal tension in the shear wall, similar to tension-field action in the plate girders. The boundary elements (The beams and columns) are required to permit the shear wall to reach excessive diagonal deformations, increasing the system ductility. The beam-column connection configuration plays an important role on deformation capacity of frame.

The beam to column connection, can be hinged or rigid. In the case of rigid connection, the moment resisting boundary frame will increase the redundancy of the lateral load resisting system (good aspect of rigid connection). On the other hand, the rigid connection increase the demand in boundary frame, and the beam-column connection may be failed, before the full yield of the web plate (bad aspect of rigid connection). In order to prevent brittle failure of beam to column connection of moment frames, two method is proposed: a) Strengthening the connection; b) Reducing the beam section strength. Both methods forces the inelastic action to take place in the beam section away from the face of the column. The reduced beam section can be achieved either by reducing the beam flange, or by reducing the beam web strength.

The investigation herein aims at studying the response of SPSWs with 3 type of reduce beam section under monotonically-applied lateral load.

3.1. Numerical modelling and acceptance criteria

In this part, three SPSW with a circular, elliptical and slotted holes in beams, was modeled. The beam to column connections was considered rigid. In the numerical model, finite strain iso-parametric shell element, SHELL 181, are used to represent the both frame members and infill plate whose dimensions are given in Tables 1, 2. Values of the yield stress, ultimate tensile stress and elastic modulus are given in Table 3. The loading was applied by subjecting the models to monotonically increasing lateral displacement. The Full Newton-Raphson method was used in the solution of non-linear equilibrium equations.

Since the beam to column connection is done by welding, the initiation of plastic strain at the connection faces can cause fracture and the first acceptance criteria is based on limiting the plastic strains at the face of connection to small values, in the finite element model. The other acceptance criteria is to limit the plastic strain to ε_u=0.14, for steel shear panel and for the beam (out of connection).

Fig. 3 shows the parameters related to the geometry of the hole. In Table 4 the details of the models can be seen. Figs. 4–8 show the 3D models.

3.2. Analysis results

The resulting lateral force - displacement curves from the numerical studies of all models is shown in Fig. 9.

Three aspects of the models can be discussed: strength; initial stiffness and ductility.

3.2.1. Stiffness

The boundary beam section reduction can cause to reduction of the flexural and shear stiffness of the beam, resulting in the reduction of lateral stiffness. This reduction can be due to the reduction of the stiffness of boundary frame itself or due to change of wall-frame interaction. As can be seen in the Fig. 9, the initial stiffness of the slotted model is close to the initial stiffness of the prototype model, while other models have reduced initial stiffness.

In the RBS model the beam flanges are reduced resulting in the reduction of moment of inertia of the beam and so the reduction of the