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Strip Model Analysis for Steel Plate Shear Walls in Earthquake Resistant Structures

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Abstract. Unstiffened Steel Plate Shear Walls (SPSWs) are very effective structural systems designed to resist lateral forces. SPSW systems consist of thin web plates infilled within frames of steel horizontal and vertical boundary elements. The thin unstiffened web plates are expected to buckle in shear and to develop diagonal tension field after buckling under the action of horizontal loads. For unstiffened steel plates, buckling in shear occurs in the elastic range at low stress levels. This behaviour provides strength, stiffness and ductility and allows to have an appropriate level of energy dissipation through tension yielding of the web plates. This paper assesses the inelastic structural response and behaviour of Steel Plate Shear Wall systems using both a modified strip model approach and a new simplified strip model for only beam connected SPSWs. Both models are developed with plasticity concentrated elements and the performed analyses include the nonlinear behaviour of strips, also considering the compressive forces effects over the strip model elements. This research indicates fundamental aspects of the seismic performance of Steel Plate Shear Wall systems, such as energy dissipation capacity, panel ductility demand, seismic inter-story drift and design load demands in Vertical Boundary Elements (VBE) and Horizontal Boundary Elements (HBE) of the frame. The results obtained from the use of these models are compared with selected experimental and numerical results to enrich the research conclusions.

Introduction

It is well know that unstiffened Steel Plate Shear Walls (SPSWs) have proven to be structural systems suitable to resist horizontal loads due to either earthquake events or wind actions [1, 2, 3, 4]. Since the first implementations and investigations, many analytical, numerical and experimental research works were developed around the world in order to attempt a more deeply understand of the overall structural response and nonlinear behaviour of SPSW structural systems [5, 6, 7, 8].

The conventional and more diffused version of SPSWs consists of one or more thin infill steel web plates surrounded by horizontal and vertical boundary elements (HBEs and VBEs, respectively) of the steel frame, which are adequately anchored to the plates. One or more bays and one or multiple storeys can form these systems. The beam-to-column connections can be either hinged (shear connection only) or moment-resisting joints.

When the structure is subjected to incremental lateral loads, the thin web infill steel plates are expected to buckle in shear and to develop a post-buckling Diagonal Tension Field (DTF). For unstiffened thin infill steel web plates, the buckling phenomena in shear occurs at low load levels in the elastic range and, therefore, a characteristic pattern of waves is formed on the plate with a certain inclination with respect to the vertical direction [9, 10, 11].

The mechanics of this behaviour provide to the structure high levels of strength, initial lateral stiffness [12] and ductility, allowing also having an appropriate level of energy dissipation capacity, with stable and regular hysteretic cycles, through the tension yielding of web infill plates when the structure is subjected to cyclic reversal loads. In addition, the SPSWs have structural redundancy and certain comparative advantages in terms of lower self-weight compared to equivalent reinforced concrete shear walls.

In recent years, a novel proposal of only beams connected SPSWs (herein called as SPSWs-BC) was developed and investigated. For this kind of structures, the thin steel web plates are only connected to the surrounding frame HBE by adequate connection systems. So, the structural configuration of SPSWs-BC tends to reduce the high flexural and shear demands over the VBE imposed by post-buckling response of infill steel plates. Additionally, these structures help to prevent potential damage and undesirable instability effects, such as local or overall buckling over these elements [13, 14].

The accuracy and refined modelling of the structural response and post-buckling behaviour of SPSWs and SPSWs-BC is a very complex task, because it involves a highly nonlinear problem characterised by large deformations. The recent structural design codes and standards require considering with sufficient accuracy the nonlinear response of the structures [15, 16]. Moreover, the development of simplified and expeditious analysis models, that are available to the designers for preliminary structural analysis through conventional and traditional specific programmes, are needed.

In order to both carry out simplified structural analysis and obtain a sufficiently accurate prediction of the inelastic behaviour and response of SPSWs, an analytical model called strip model was developed [1, 17]. This model replaces the web infill steel plates by several (generally 8 to 10) only tension steel strips, hinged to the HBE and VBE, which simulate the post-buckling DTF on the plate.

Since the first version of the strip model technique, several proposals have been made to modify it. Such modifications mainly try to introduce into the structural analysis the effect of the compression forces due to DTF over the plate [6, 18]. In fact, in most of the case studies, it has been shown that these compression components cannot be neglected. This kind of analytical model is worldwide accepted and has been adopted for simplified structural analysis by several design codes, standards and practical specifications [15, 16].

The main response characteristics of both SPSWs and SPSWs-BC are so advantageous to make these structural systems very suitable for seismic design. For seismic resistant structures, the corresponding HBEs and VBEs can be made of either steel cross sections or reinforced concrete framed elements. SPSW systems can be applied either into new structures or for strengthening or retrofitting interventions on existing seismically vulnerable or damaged structures [19, 20].

This investigation paper assesses the inelastic structural response and behaviour of SPSWs in earthquake resistant structures by using both a modified conventional strip model approach and a new simplified strip model for SPSWs-BC. Both strip models are developed and implemented within SeismoStruct v.7.0.0, a finite element nonlinear analysis software [21], by using concentrated plasticity zero length elements.

The analytical models developed are simple for the computational implementation and have capability to consider the compressive forces effects over the thin steel plates. The performed analysis includes the nonlinear behaviour of tension strips and compression struts through the adequate calibration of the nonlinear links elements.

The research remarks fundamental aspects of the seismic performance of SPSW systems, such as energy dissipation capability, web plate ductility demand, seismic inter-story drift of the selected case studies and design load demands in Vertical Boundary Elements (VBE) and Horizontal Boundary Elements (HBE) of the frame.

In conclusion, the results obtained from the use of both strip models are compared and validated based on some selected experimental and numerical results to enrich the research findings.

Strip Models

In order to obtain a simplified and expedite numerical computational tool, able to perform the preliminary and simplified structural analysis of SPSW earthquake resistant structures under monotonic incremental static load analysis, two modified and simplified strip models have been developed.

Modified Strip Model for conventional SPSWs. The first model is developed to represent the structural response and nonlinear behaviour of conventional SPSWs. It consist of a concentrated plasticity strip model (called in this work SMPC5), configured with five hinged tension strips and five hinged compression struts (S_1 to S_3), arranged respectively along the directions of the main tensile and compression stresses, which are connected to the HBE and VBE structural members. These strips are geometrically inclined with an angle β with respect to the vertical direction.

The overall nonlinear response and post-buckling behaviour of web infill thin steel plates are concentrated in the extreme strip placed link elements, called L_1, L_2 and L_3 (see Fig.1), which are implemented using zero-length nonlinear elements with asymmetric bilinear constitutive law (SeismoStruct bl_asm link element). Fig.1 shows the schematic representation of the physical model of a typical panel having one bay framed structure developed on one floor. In this figure, L and h are the distances between VBE and HBE axis, respectively. The position of the lateral strips S_1 is given by the parameter a_1, while the strips S_3 and the links L_2 over the HBE are provided by the parameter $a_2 = L\text{-}a_1$.

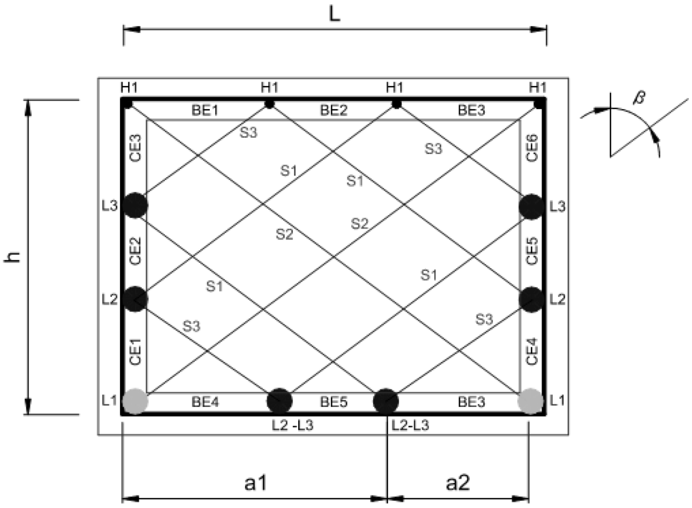


Fig. 1. Geometrical configuration of the SMCP5 Strip Model placed into a one floor-one bay framed structure

In Figure 1 BE1 to BE3 and CE1 to CE6 are implemented by inelastic frame force based element, (SeismoStruct infrmFB), S1 to S3 are inelastic truss fibre elements (SeismoStruct truss element) and H1 is a zero-length link element representing a perfect hinged connection at the end of strips and struts. The model is configured with a modified inclination angle of tension strips (see Fig.1), which is calculated by the following equation:

$$tg\beta = \frac{L}{h} = \frac{a_1 + a_2}{h} \tag{1}$$

The strip model is able to capture in a simplified way the structural behaviour under monotonic lateral incremental loads, that represent the actual behaviour of the SPSW structures in terms of their global response under the action of earthquake loads.

Strip Model for SPSWs-BC. The second model is developed to represent the structural response and nonlinear behaviour of novel SPSWs-BC. The presented model consists of a concentrated plasticity strip model (called in this work MSM03-BC), geometrically arranged with three hinged tension strips and three hinged compression struts (S4) at each incremental load direction. The strips are oriented with an angle ϑ with respect to the vertical direction, which conforms to the tension field inclination of partially connected web plates.

In the same way as in the previously described model, the nonlinear behaviour of web infill thin steel plates is concentrated at links L_4 (see Fig.2), which are implemented using zero-length nonlinear link elements with an asymmetric bilinear constitutive law. Fig.2 shows the schematic representation of the physical model of a panel within a typical one floor - one bay framed structure. In this picture L_{bc} and h_{bc} are the effective width and height of the only beam connected infill steel plate, respectively, while L_t is the length of either bolted or welded connection devices between the infill web steel plates and the corresponding top and bottom HBE of the frame.

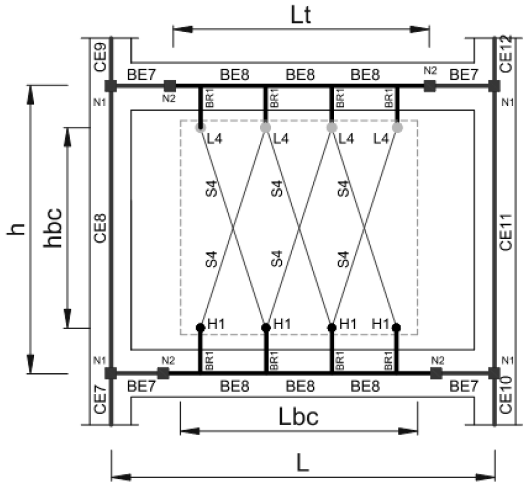


Fig. 2. Geometrical configuration of the MSM03-BC Strip Model placed into a one floor-one bay framed structure

In the same Fig.2 it can be observed the other various structural elements that make up the presented strip model. In particular, BE7, BE8 and CE7 to CE12 are inelastic frame force based elements, (SeismoStruct infrmFB), S4 strips are inelastic truss fibre elements (SeismoStruct truss element) and H1 is a zero-length link element representing a perfect hinged connection. The eccentricity between the HBE axis and the centroid axis of the connecting joints with the plate is modelled by BR1 elements, which are rigid internal link with six relative degrees of freedom restrained. In the present model, the inclination angle θ of tension strips (angle of tension field with respect to the vertical direction), is calculated according to the proposal of previous available research works [22] by the following equation:

$$\theta = \gamma tan^{-1}\left(\frac{L_{bc}}{h_{bc}}\right) \tag{2}$$

where γ is a non-dimensional parameter calculated according to the following expression:

$$\gamma = 0.55 - 0.03\left(\frac{L_{bc}}{h_{bc}}\right) \geq 0.51 \tag{3}$$

The careful definition of θ is associated with the posterior definition of fundamentals parameters of the model, such as the effective width L_f of the partially connected web plate, which is evaluated by the following equation:

$$L_f = L_{bc} - h_{bc}\, tan\theta \tag{4}$$

The effective width of each strip L_s is evaluated by the following equation:

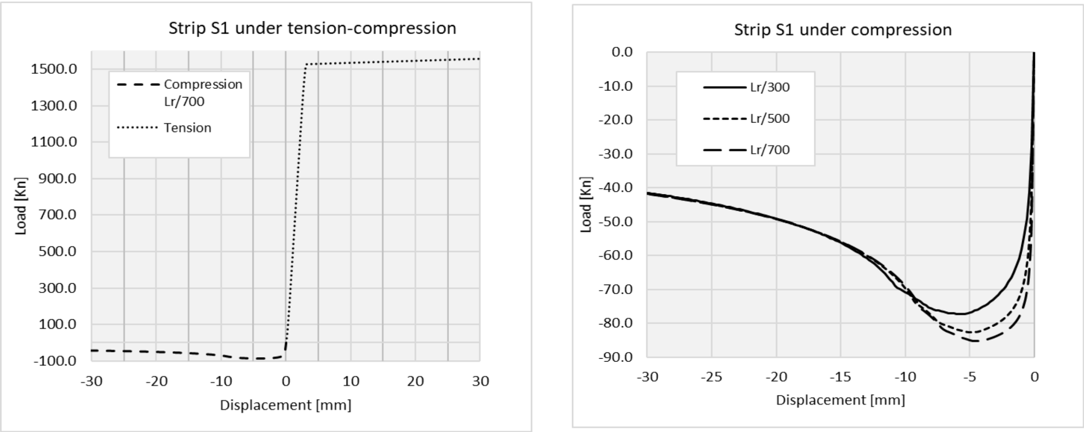
$$L_s = \frac{Lf}{n_s} \tag{5}$$

where n_s is the number of strips at each load direction.

Characterization of the Nonlinear Response of Compression Struts

In order to adequately calibrate the bilinear constitutive law used in the characterization of the link elements that concentrate the nonlinear behaviour of the compression struts (SeismoStruct bl_asm link element), a nonlinear incremental load analysis in compression for the braces under analysis has been performed. In the model, the intermediate crossing points of the analysed strut with the tension strips are laterally restrained. The numerical computational model of compression struts is developed with initial imperfection patterns close to the first buckling mode of the same strut.

The incremental compression analysis has been performed over a steel strip S_1 with a rectangular cross section of 0.006m x 0.769m. The steel is characterised by an elastic longitudinal modulus $E = 2.0\text{x}10^8$ kPa and a yield stress $f_y = 340000$ kPa, with a hardening parameter by deformation of 0.002. Fig.3 (a) shows the tension-compression vs. longitudinal displacements response diagram of strip S_1 characterised by the SMCP5 strip model. Fig.3 (b) shows the compression behaviour of the strip S_1 for three initial imperfections $L_r/300$, $L_r/500$ and $L_r/700$, where L_r is the length of S_1.



(a) (b)

Fig. 3. Strip model for the SMCP5 links: (a) tension-compression response and (b) parametric analysis of the compression response for three initial imperfections for the S_1 strips

Numerical Calibration of Literature Test Results

In order to validate the structural response of the strip models developed, some numerical and experimental results available from previous researches on both SPSWs and SPSWs-BC have been selected.

SMCP5 Strip Model. Aiming at checking the accuracy prediction of overall nonlinear response of this model, the results of the numerical research work performed by Guo et.al. have been taken into account [23]. The structure analysed consists of a single bay - one storey pin-ended steel framed structure with infill steel thin web plates. In order to have a rigid element, the frame beam has a solid rectangular cross-section of 500x500 mm, while the frame columns have a steel H-shaped cross-section with 350x20 mm flanges and a 420x15 mm web. The inter-storey height is 1800 mm and the bay of the selected frame is 2700 mm wide in order to obtain a span-to-height ratio $\beta = 1.5$. The steel adopted has an elastic longitudinal modulus $E = 2.0\text{x}10^8$ kPa, a yield stress $f_y = 340000$ kPa and a Poisson module $\nu = 0.30$.

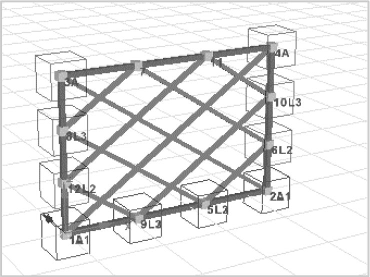
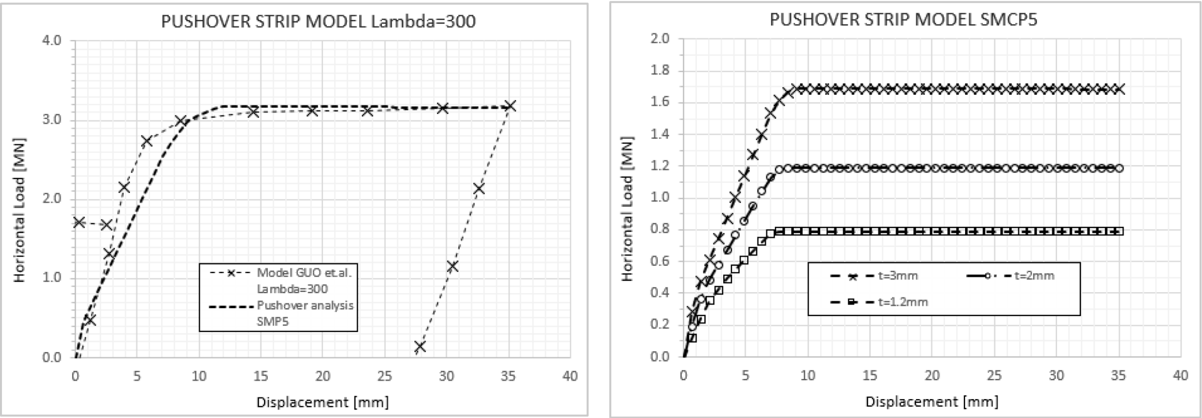


Fig. 4. Implementation in SeismoStruct of the SMCP5 strip model

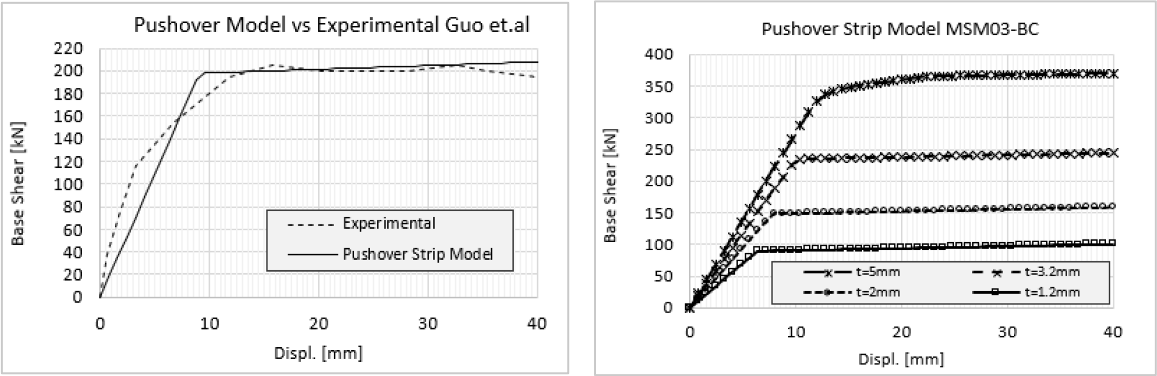
Fig. 5 (a) shows a comparison chart between the skeleton curve derided from the SPSW nonlinear response of the Guo et al.'s test [23] and the structural nonlinear response of the SMCP5 strip model under incremental lateral horizontal load at the top level of the frame. Fig. 5 (b) shows a comparison chart of the nonlinear behaviour of the same frame with three different plate thicknesses (1.2 mm, 2 mm and 3 mm).



(a) (b)

Fig. 5. SMCP5 strip model response: (a) validation with the skeleton curve of the Guo et al.'s test [23]; (b) comparison chart among three plates with different thicknesses

MSM03-BC Strip Model. The accuracy level of the MSM03-BC strip model has been evaluated and adequately validated based on the skeleton curve derived from a previous research work developed by Guo et al. [13]. The validation model selected consists of a pin-ended plate specimen having plane dimensions of 1100 mm by 1100 mm and thickness of 2.7 mm.



(a) b)

Fig. 6. MSM03-BC strip model response: (a) pushover validation with the skeleton curve of the Guo et al.'s test [13]; (b) comparison chart among plates with four different thicknesses

Fig. 6 (a) shows a comparison chart between the skeleton nonlinear response curve of the selected reference test [13] and the structural nonlinear response of the MSM03-BC strip model under incremental lateral horizontal load at the top level of the frame. In the same way, Fig. 6 (b) shows a comparison chart of the nonlinear behaviour of the analysed frame with four infill plates having different thicknesses (1.2 mm, 2 mm, 3.2 mm and 5 mm) to see the effect of this parameter change over the variation of both the ultimate capacity load and the initial lateral stiffness of the structure.

Conclusions

A numerical assessment of the inelastic response and behaviour of SPSWs applied to seismic resistance structures has been herein presented. The analysis included both the conventional Steel Plate Shear Walls connected to the surrounding structural members (HBE and VBE) and the novel configuration of steel infill web plates only connected to upper and bottom beam elements of the external steel frame.

In both cases, simplified strips models for preliminary structural analysis, having the ability to adequately represent the response and nonlinear behaviour of the thin infill web steel plates, have been developed. The models consider the effect of compression forces on the plate with concentrated plasticity link elements calibrated on the results of numerical compression analysis on individual compression struts.

The strip models presented capture correctly the initial lateral stiffness and the ultimate load capacity of the studied structures. From the incremental analyses carried out it has been possible to show aspects related to the ductility criteria of SPSWs, as well as to compare responses and nonlinear behaviour of both SPSWs and SPSWs-BC.

The corresponding numerical analysis performed with the SeismoStruct Finite Element software based on presented models calibrated according to available literature tests have confirmed the effectiveness of the strip models presented to carry out preliminary analysis on SPSWs structural solutions. The investigations demonstrated that the simplified strip models are suitable for the representation of the nonlinear behaviour of seismic resistant structures that include steel web infill plates in terms of ductility and ultimate capacity load.

Although the simulation of literature tests has been successfully done, it is necessary to carry out deeper studies to increase the understanding and validation of the proposed numerical models mainly by addressing parametric analysis towards both the analysis of the several variables involved and the study of reversible cyclic loads on the structure.

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