Influence of coupling beams to the energy dissipation of coupled steel plate shear wall

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Abstract. Shear Plate Shear Wall (SPSW) is a lateral force resisting system that is usually used in high seismic regions. Opening can be accommodated by using coupled steel plate shear wall (CSPSW) where two or more SPSWs are placed adjacently and are connected by coupling beams. Maximum displacement, shear load capacity and energy dissipation are affected by the dimension of the coupling beams. The construction cost of the building can be reduced vastly by optimizing the size of the coupling beams where the capability of CSPSW to resist the earthquake is maximized. Thus, the objective of this study is to determine the behaviour of maximum displacement, shear load capacity and energy dissipation of the CSPSW when the width, depth and length of the coupling beams are varied. Fourteen CSPSW models were analysed by ABAQUS software, where the models were subjected to lateral cyclic loading as accordance to ATC24. Maximum displacement of the CSPSW was not affected by the dimensions of the coupling beams. Shear load capacity was increased as either the width or the depth of the coupling beam was increased, and achieved its maximum value when the length of the coupling beam was 1000 mm. The optimum width, depth and length of the coupling beam to maximize the energy dissipation of the CSPSW models were 200 mm, 1000 mm and 1000 mm, respectively.

1. Introduction

The Steel Plate Shear Wall (SPSW) is an efficient and economical structural system for resisting earthquake that had been widely used for decades in countries such as Japan, Canada and U.S.A. SPSW is composed of an infilled plate that is enclosed and joined to horizontal boundary elements (HBE) and vertical boundary elements (VBE). Boundary elements must be completely anchored to ensure that these web plates buckle under diagonal compression first in order to cause the web plate to be completely yield in tension. SPSW has great initial elastic stiffness, better bearing capacity, high redundancy, excellent ductility and energy dissipation capacity [1, 2]. This yielding mechanism dissipates a substantial amount of energy and exhibits excellent ductility [3, 4, 5]. Furthermore, steel frame-steel plate shear wall structures (SF-SPSW) have a high collapse-resistant capability [6]. Two methods can be employed to increase the shear strength which are, increasing the web plate thickness and increasing the bay length. Increasing the thickness of web plate leads to the increase of the stresses in boundary elements which contributes to brittle failure of columns as well as, prohibiting the occurrence of buckling of the web plate. However, the infill thin steel plate of SPSW is prone to buckle even at elastic stage which also causes load noise accompanied with poor comfort [7]. Increasing the bay length reduces the stresses in HBE. According to American Institute of Steel Construction, 2010 (AISC 341-10), larger
HBE that is required in the design can be avoided if the ratio of the bay length to story height ratio ranges between 0.8 to 2.5 [8].

The long bay length of SPSW and the placement of SPSW that is specified by the architect to be at the building core may obstruct human access from one part to another part of the building. Thus, perforation of SPSW is required to enable human access as well as to serve as window that provides natural lighting, unobstructed outdoor view and ventilation. Unfortunately, perforating SPSW has been proved in research to decrease energy dissipation of the system [9]. The accommodation of openings for doorways and elevators can also be provided by the placement of two adjacent SPSWs that are connected by coupling beams (CB) to form a coupled steel plate shear wall (CSPSW). Three key factors contributing to the desirability of the CSPSW are architectural flexibility, material efficiency, and overturning stiffness [10].

However, in improving CSPSW, fabrication costs will become a potential drawback for their use. Another option to improve CSPSW is to optimize the dimension of CSPSW to maximize the energy dissipation of the system. Thus, the objective of this study is to obtain the pattern of energy dissipation of the CSPSW when the dimensions of coupling beams are varied.

2. Methodology

CSPSW model that was analysed is composed of two SPSWs that were connected to one another by coupling beams at every level of the building. The same sections are used for VBE and HBE of all models which are steel box hollow section of 500x500x20 mm and steel I-beam of 400x300x8x20 mm, respectively, as shown in Figure 1. Boundary elements prevent the steel plate from being imposed by gravity load as the steel plate function is to carry only lateral load. The lateral load causes the steel plate to form tension field that acts like a diagonal brace. The SPSWs at each level of the model are 4 m high and 3.2 m wide. ABAQUS finite element software was used to model and analyse the CSPSWs models where horizontal and vertical boundary elements were modelled by using wired element while the infill plate was modelled by using reduced integrated shell element. The reduced integrated formulation was adopted to produce more accurate results and minimize computing time. The infill plate used A36 steel while the other components which are the boundary elements and the coupling beam used A992 steel. The yield stress of A36 steel and A992 steel are 250 MPa and 345 MPa, respectively.

The dimensions of the cross section of the coupling beam for each of the CSPSW model are tabulated in Table 1. The dimension of the cross section that each variable represents is shown in Figure 2. The fourteen models that were studied were divided into three groups: group 1, 2 and 3, depending on what the parameter of interest is. Group 1 models have varying width of the coupling beams which are 100 mm, 200 mm, 300 mm and 400 mm. Group 2 models have varying depth of the coupling beams which are 400 mm, 600 mm, 800 mm, 1000 mm and 2000 mm. Last but not least, group 3 models have varying length of the coupling beams which are 0.5 m, 1 m, 1.5 m, 3 m and 5 m.
Figure 1. SPSW model with coupling beam at different length, width and depth that will be studied.

Figure 2. Cross-section of coupling beam.
Table 1. Specification of coupling beam

| GROUP | COUPLING BEAM | SPECIFICATION (all unit in mm) | LENGTH (mm) |
|-------|---------------|---------------------------------|-------------|
| 1     | CBB1          | 400x100x8x20                    | 1500        |
|       | CBB2          | 400x200x8x20                    | 1500        |
|       | CBB3          | 400x300x8x20                    | 1500        |
|       | CBB4          | 400x400x8x20                    | 1500        |
| 2     | CBD1          | 400x300x15x30                   | 1500        |
|       | CBD2          | 600x300x15x30                   | 1500        |
|       | CBD3          | 800x300x15x30                   | 1500        |
|       | CBD4          | 1000x300x15x30                  | 1500        |
|       | CBD5          | 2000x300x15x30                  | 1500        |
| 3     | CBL1          | 400x240x8x20                    | 500         |
|       | CBL2          | 400x240x8x20                    | 1000        |
|       | CBL3          | 400x240x8x20                    | 1500        |
|       | CBL4          | 400x240x8x20                    | 3000        |
|       | CBL5          | 400x240x8x20                    | 5000        |

Cyclic lateral load was applied at the top end of the model. The cyclic load that was applied to the CSPSW models was in accordance to the load protocol outlined by ATC24 – Guidelines for Cyclic Seismic Testing of Components of Steel Structures [11] as depicted in Figure 3.

![Load Protocol](image)

**Figure 3.** Load protocol for lateral loading applied to CSPSW models
3. Results and discussion
Hysteretic curve which is a graph of load-displacement relation curve was plotted for each model and energy dissipation was determined. Table 2 tabulates the displacement, shear load capacity and energy dissipation for all models.

Table 2. Maximum displacement, shear load capacity and energy dissipation of all models.

| Group | Model | Size of Coupling Beam d x b x t (all unit in mm) | Length of Coupling Beam (mm) | Maximum Displacement (mm) | Shear Load Capacity (kN) | Energy Dissipation (kNm) |
|-------|-------|-----------------------------------------------|-----------------------------|---------------------------|--------------------------|--------------------------|
| 1     | CBB1  | 400x100x8x20                                 | 1500                        | 66.16                     | 6568.25                  | 1600.29                  |
|       | CBB2  | 400x200x8x20                                 | 1500                        | 66.01                     | 6795.46                  | 1739.76                  |
|       | CBB3  | 400x300x8x20                                 | 1500                        | 65.89                     | 6863.15                  | 1467.65                  |
|       | CBB4  | 400x400x8x20                                 | 1500                        | 65.86                     | 7023.4                   | 1601.42                  |
| 2     | CBD1  | 400x300x15x30                                | 1500                        | 65.82                     | 7117.42                  | 1654.53                  |
|       | CBD2  | 600x300x15x30                                | 1500                        | 65.8                      | 7323.41                  | 1825.82                  |
|       | CBD3  | 800x300x15x30                                | 1500                        | 65.78                     | 7372.22                  | 1606.9                   |
|       | CBD4  | 1000x300x15x30                               | 1500                        | 65.78                     | 7481.39                  | 1908.08                  |
|       | CBD5  | 2000x300x15x30                               | 1500                        | 65.78                     | 7611.09                  | 1666.54                  |
| 3     | CBL1  | 400x240x8x20                                 | 500                         | 65.84                     | 6677.47                  | 1313.77                  |
|       | CBL2  | 400x240x8x20                                 | 1000                        | 65.87                     | 6819.71                  | 1553.77                  |
|       | CBL3  | 400x240x8x20                                 | 1500                        | 65.96                     | 6792.9                   | 1400.25                  |
|       | CBL4  | 400x240x8x20                                 | 3000                        | 66.22                     | 6665.27                  | 1501.05                  |
|       | CBL5  | 400x240x8x20                                 | 5000                        | 66.42                     | 6550.65                  | 1531.95                  |

3.1. Effect of breadth and depth of coupling beam
Maximum displacement of all models were similar, while shear load capacity increased as either the width or the depth of the coupling beams was increased (Table 2). Energy dissipation of model CBB2 which had coupling beam width of 200 mm is higher than energy dissipation of model CBB1 that had coupling beam width of 100 mm. However, as the width of the coupling beam was increased to 300 mm (model CBB3), energy dissipation decreased despite the increment of the shear load capacity. This is due to coupling beam became stiffer and had smaller value of displacement for all cycles of the lateral load applied except for the last few cycles as depicted in hysteretic curve shown in Figure 4(c). Similar behaviour was observed for model CBB4 which had coupling beam width of 400 mm. The higher energy dissipation of model CBB4 compared to model CBB3 was caused by the higher shear load capacity of model CBB4 compared to model CBB3. Thus, model CBB2 has the most optimum width of coupling beam as the energy dissipation capacity was maximized compared to all models in Group 1.
Figure 4. Hysteretic curve of (a) model CBB1 (b) model CBB2 (c) model CBB3 (d) model CBB4

The energy dissipation of model CBD2 that has coupling beam depth of 600 mm was higher compared to model CBD1 that has coupling beam depth of 400 mm. The higher shear load capacity together with the higher displacement range for each loop in the hysteresis curve of model CBD2 (Figure 5(b)) contributed to the higher energy dissipation of this model compared to model CBD1. The narrow width of most loops in the hysteresis curve of model CBD1 (Figure 5(a)) resulted smaller displacement range which caused lower energy dissipation compared to model CBD2. As the depth of the coupling beam was increased to 800 mm (model CBD3), energy dissipation was reduced to the minimum value. Careful examination of the loops in hysteresis curve of model CBD3 (Figure 5(c)) shows that each subsequent loop shifted to the right, but the displacement range of each loop remained small except for the last two loops, that resulted in the drop of the energy dissipation value. When the depth of the coupling beam was 1000 mm (model CBD4), the energy dissipation was the maximum compared to all models in Group 2. This is due to the increment of both the shear load capacity and the displacement range of all loops in the hysteresis curve as shown in Figure 5(d). The larger depth of the coupling beam allows the stresses being transmitted efficiently from one SPSW to another resulting better utilization of the yielding mechanism of the infill plate of both SPSWs. However, increasing the depth of the coupling beam to 2000mm (model CBD5) caused a large decrease of the energy dissipation. The large depth of the coupling beam had caused the whole CSPSW model to become stiffer as can be seen from the small displacement range of most loops in the hysteresis curve (Figure 5(e)). The
increment of breadth and depth of coupling beam have affected the flanged-web intersection that exhibits cyclic behaviour [12]. Thus, the most optimum depth of the coupling beam to maximize the energy dissipation is 1000mm.

Figure 5. Hysteretic curve of (a) model CBD1 (b) model CBD2 (c) model CBD3 (d) model CBD4 (e) model CBD5
3.2. Effect of length of coupling beam

Increasing the length of the coupling beam from 500 mm (model CBL1) to 1000 mm (model CBL2) had caused both the shear load capacity and energy dissipation to increase (Table 2). However, shear load capacity decreased as the length of the coupling beam was increased to 1500 mm (model CBL3), and progressively decreased as the length of the coupling beam was increased (model CBL4 and CBL5). The long length of the coupling beam had caused the two SPSWs to work individually instead of one structure as when the length of the coupling beam was short [13]. Energy dissipation of model CBL3 is the least due to the displacement range of each loop in the hysteresis curve became the smallest among all models in Group 3 (Figure 6(c)). As the length of the coupling beam was increased further (model CBL4 and CBL5), energy dissipation increased progressively as the displacement range of the loops in the hysteresis curve increased. Thus, the most optimum length of coupling beam is 1000 mm.
Figure 6. Hysteretic curve of (a) model CBL1 (b) model CBL2 (c) model CBL3 (d) model CBL4 (e) model CBL5

Model CBL3 with coupling beam width of 240mm had the lowest shear load capacity and energy dissipation among all models (Table 3). Increasing the coupling beam width to 300 mm (model CBB3) increased the the shear load capacity and energy dissipation slightly, but increasing the thickness of both the flange and web of the coupling beam (model CBD1) increased both shear load capacity and energy dissipation substantially. Maximum increment of both the shear load capacity and energy dissipation was achieved when the depth of the coupling beam was increased to 1000 mm (model CBD4). Model CBD4 had the largest shear load capacity and energy dissipation among all CSPSW models analysed in this study.

| Model | Size of Coupling Beam d x b f x t w x t f (all unit in mm) | Length of Coupling Beam (mm) | Shear Load Capacity (kN) | Energy Dissipation (kNm) |
|-------|----------------------------------------------------------|-----------------------------|--------------------------|--------------------------|
| CBB2  | 400x200x8x20                                             | 1500                        | 6795.46                  | 1739.76                  |
| CBL3  | 400x240x8x20                                             | 1500                        | 6792.9                   | 1400.25                  |
| CBB3  | 400x300x8x20                                             | 1500                        | 6863.15                  | 1467.65                  |
| CBD1  | 400x300x15x30                                            | 1500                        | 7117.42                  | 1654.53                  |
| CBD4  | 1000x300x15x30                                           | 1500                        | 7481.39                  | 1908.08                  |

4. Conclusion
This study explored the behaviour of shear load capacity and energy dissipation of CSPSW with different depth, width and length of the coupling beams. Shear load capacity was increased as either the width or the depth of the coupling beam was increased. Shear load capacity achieved its maximum value when the length of the coupling beam was 1000 mm but decreased progressively as longer coupling beams was used.

Energy dissipation achieved its maximum value as the width of the coupling beam was increased from 100 mm to 200 mm for group 1 models. Model CBD4 that has the coupling beam depth of 1000 mm had the largest value for energy dissipation among group 2 models. Increasing the depth of the coupling beam to 2000 mm caused the CSPSW to become stiffer and thus lower the energy dissipation. Energy dissipation was maximized when the length of the coupling beam was 1000 mm. The yielding
mechanism of the infill plate contributes to the energy dissipation of CSPSW. The dimensions of the coupling beams that influenced the energy dissipation are depth and the thickness of the flange and web of the coupling beams followed by the width and length of the coupling beams.

Acknowledgements
The study was funded by the Ministry of Education Malaysia and Research Management Centre, Universiti Teknologi Malaysia Fundamental Research Grant Scheme No. R.J130000.7851.5F052.

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