COMBINATION OF STEEL PLATE SHEAR WALLS AND TIMBER MOMENT FRAMES FOR IMPROVED SEISMIC PERFORMANCE

A. Iqbal(1), B. Todorov(2), AHMM. Billah(3)

(1) Assistant Professor, University of Northern British Columbia, asif.iqbal@unbc.ca
(2) Graduate Student, Lakehead University, btodorov@lakeheadu.ca
(3) Assistant Professor, Lakehead University, muntasir.billah@lakeheadu.ca

Abstract

Recent interests in adopting sustainable materials and developments in construction technology have created a trend of aiming for greater heights with timber buildings. With the increased height these buildings are subjected to higher level of lateral load demand. A common and efficient way to increase capacity is to use shearwalls, which can resist significant part of the load on the structures. Prefabricated mass timber panels such as those made of Cross-Laminated Timber (CLT) can be used to form the shearwalls. But due to relatively low stiffness value of timber it is often difficult to keep the maximum drifts within acceptable limit prescribed by building codes. It becomes necessary to either increase wall sizes to beyond available panel dimensions or use multiple or groups of walls spread over different locations over the floor plan. Both of the options are problematic from the economic and functional point of view. One possible alternative is to adopt a Hybrid system, using Steel Plate Shear Walls (SPSW) with timber moment frames. The SPSW has much higher stiffness and combined with timber frames it can reduce overall building drifts significantly. Frames with prefabricated timber members have considerable lateral load capacity. For structures located in seismic regions the system possesses excellent energy dissipation ability with combination of ductile SPSW and yielding elements within the frames. This paper investigates combination of SPSW with timber frames for seismic applications. Numerical model of the system has been developed to examine the interaction between the frames and shear walls under extreme lateral load conditions. Arrangements of different geometries of frames and shear walls are evaluated to determine their compatibility and efficiency in sharing lateral loads. Recommendations are presented for optimum solutions as well as practical limits of applications.

Keywords: Timber moment frame, Steel plate shear wall, Seismic Performance, Interstorey drift

1. Introduction

Over the last decade, Canadian construction industry has experienced significant increase in constructing timber buildings with greater heights. Timber skyscrapers are now a common interest among the architects, developers, and structural engineers. Origine Point-aux-Lievres Ecocondos in Quebec City, the 54-metre-tall UBC Brock Commons student residence in Vancouver, BC, and the 29.5-metre-tall Wood Innovation and Design Centre (WIDC) in Prince George, BC are few examples of the tallest contemporary wood buildings in Canada. In response to growing support for timber skyscrapers throughout Canada and around the world, the provincial government of British Columbia has changed its building codes, effectively doubling the height limit for wood-frame buildings to 12 storeys. Other provinces and territories in Canada are also following this and it is expected that the National Building Code of Canada will follow the same creating more opportunities for taller timber structures.

There are several benefits of using taller timber structures such as efficient footprint, faster and safer on-site construction, improved structural and seismic performance, and tight envelopes [1]. Albeit these advantages are encouraging, the increased height of timber buildings are likely to experience significant increase in lateral load demand such as wind and earthquake. A common and efficient way to increase capacity is to use shearwalls, which can resist significant part of the lateral load on the structures. Prefabricated mass timber panels such as those made of Cross-Laminated Timber (CLT) can be used to form the shearwalls. But due to relatively low stiffness value of timber it is often difficult to keep the maximum drifts within acceptable limit prescribed by building codes. It becomes necessary to either increase wall sizes to beyond available panel dimensions or use multiple or groups of walls spread over different locations over the floor plan. Both of the options are problematic from the economic and functional point of view.

In recent years, hybrid steel-timber structures have attracted a lot of attentions and good number of research studies are available [2-4]. In addition, researchers have dedicated significant efforts investigating the seismic performance of light timber frame structures and mass timber structures using CLT panels [5-7]. Most of these studies are focused on steel frames with CLT infills and hybrid steel-timber beam-column joints. However, it may not always be possible to satisfy the maximum drift limit prescribed by building codes only with CLT shear walls or hybrid steel-timber moment resisting frame. One possible solution is to combine Steel Plate Shear Walls (SPSW) with timber moment frames. The SPSW has much higher stiffness and, combined with timber frames, it can reduce overall building drifts significantly. The objective of this study is to explore the feasibility of a hybrid SPSW-Timber moment frame as one of the next generation of Hybrid Structures to be used to increase the height limit of timber buildings. Numerical models of 9, 12, and 15-storied hybrid SPSE-timber frame structures have been developed to examine the interaction between the frames and shear walls under lateral loading.

2. Steel Plate Shear Walls

Numerous analytical and experimental researches have shown that SPSWs can be a very efficient energy dissipation system [8-13] through cyclic yielding of the tension field that develops in the infill plate after buckling in shear. Because of the efficiency of the infill plate in carrying storey shears, it has been observed that plate thickness requirements are generally very low for mid to low-rise buildings, even under relatively severe seismic loading. Flat hot-rolled plates have been used as infill panels to form steel plate shear walls. The panels basically provide resistance to lateral load through tension capacity along diagonals. Additionally, energy dissipation can be achieved through tension yielding of the plates, particularly under cyclic loading, which makes them useful for seismic applications either for new designs or retrofit [8].

Behaviour of the steel plates include diagonal tension as described by Wagner [14] in combination with buckling in shear, observed in plate girders by Basler [15]. Built on those investigations, design concept for steel plate shear wall was proposed by Thornburn et al. [11]. That was followed by analytical and experimental work by Timler and Kulak [12], Tromposch and Kulak [13], and Driver et al. [10].

Berman and Bruneau [8] performed plastic analysis and design, followed by experimental investigation of steel plate shear walls. The findings were later summarized for design requirements by Bruneau et al. [9]. Clayton et al. [16] conducted a series of experimental studies to investigate the behaviour and appropriateness of a self-centering SPSW system using post-tensioned beam-to-column connections. They concluded that the developed system has high ductility, high initial stiffness, and recentering capabilities. Unfortunately, the SPSW system remains less attractive to practicing engineers, mainly due to the overstrength resulting from the use of much thicker than required infill plates, which is required to facilitate fabrication.

3. SPSW with Timber moment frames

With increasing demand for sustainable construction and introduction of advanced materials such as engineered wood products, there is an ongoing effort to build taller and more efficient buildings with timber. But timber has got some inherent limitations as structural material such as low stiffness and perpendicular-to-grain strength. With those constraints it often becomes impractical to design timber moment frames for cases where lateral loads are significant, such as for tall buildings. At the same time, the deflections of the frames can become excessive, raising serviceability issues.

Practitioners have opted different solutions to overcome the problem, such as addition of solid timber shear walls, used braced frames and increase moment capacity of frames with post-tensioning. A novel approach of combining steel plate shear walls with timber moment frames is proposed here. The steel plates are used as infill panels within timber moment frames in place of steel beams and columns. With accurate proportioning of the members and plates the lateral loads can be shared efficiently between the two components. At the same time, displacement compatibility can be achieved through careful connectivity and detailing.

Steel plate shear wall (SPSW) is a very effective system for resisting lateral loads due to wind and earthquakes, but the system remains less attractive to practicing engineers due to their high strength and the high forces they attract during earthquakes. Use of light-gauge steel shear walls rather than conventional shear walls with thicker hot-rolled infill plate, represents a viable and more economical alternative. Although some prior study has been conducted on steel frame-wood panel shear wall [17,18], no study has been conducted to explore the possibility of combining timber frame-steel plate shear wall system. This study is intended to explore the possibility of using light-gauge steel shear wall with timber frame that can be used as a lateral load resisting system for high-rise timber structures.

4. Design and Numerical modelling of Timber Frame-SPSW

Moment frames from three prototype buildings were selected to analyse the seismic response of the proposed hybrid SPSW-timber frame structure. In this study, a total of three building heights 9, 12, and 15-storey, timber moment resisting frame buildings were considered (Fig. 1a) without irregularity in plan (Fig. 1b). The three selected prototype buildings consist of timber frames designed to carry the gravity load with five-3.5m wide bays in the longitudinal direction and three-5m bays in the transverse direction. The height of all stories are kept constant as 3.2m for all three buildings considered in this study. The building is assumed to be located in Vancouver, BC. A preliminary design under combined dead, live, and snow loading only was performed in accordance to CSA 086-14 [19] to determine beam and column section sizes in the models. Design optimization was neglected in this building, and column sections remain consistent throughout all stories of each building.

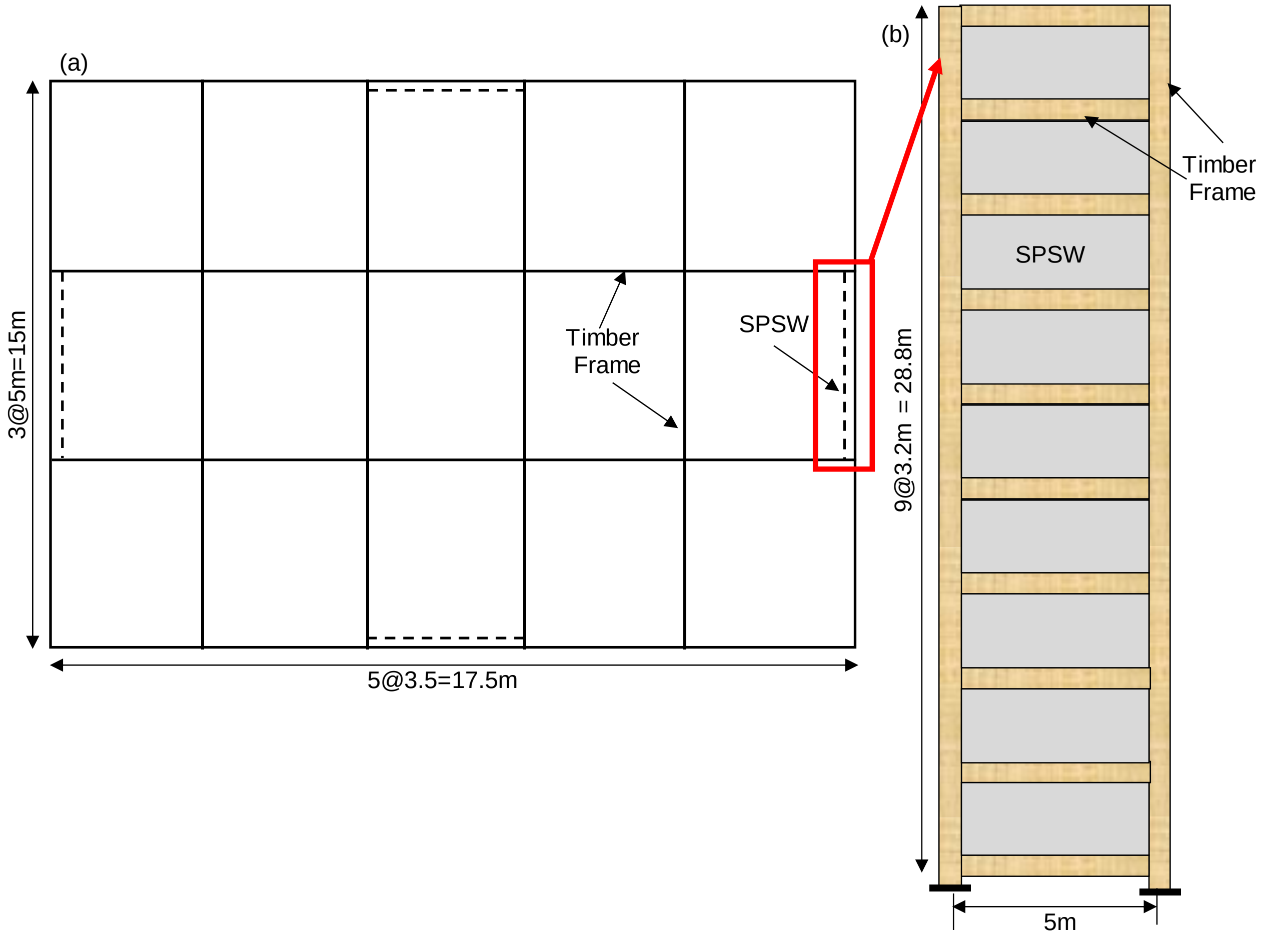

Fig. 1– (a) Plan and (b) Elevation of the SPSW-timber frame building [9 storied shown only]

For selecting the appropriate SPSW thickness, a preliminary parametric static analysis was performed to identify the suitable thickness of SPSW. Lateral loading applied to the structure was determined and distributed using the equivalent static force method according to NBCC 2015 [20]. Based on preliminary static analysis results, the use of a 2mm thick steel plate shear wall was considered for all the models in this study. Table 1 summarizes the preliminary beam column dimensions as well as the results obtained from the static analysis of the 9-storied building. It can be noticed that the use of thin infill plates provide improved seismic performance as compared to the model without SPSW. Maximum roof drift obtained from the static analysis was considered as the deciding factor for the selection of SPSW thickness. From Table 1, it can be observed that the bare timber frame experienced significant amount of maximum drift in excess of 5%. When a 1mm SPSW is considered, the maximum drift was reduced to only 0.75%. Further increasing the SPSW thickness resulted in smaller drift of 0.57% and 0.48% for 2mm and 4mm SPSW, respectively. However, in order to have a reasonable thickness of SPSW for taller frames, i.e. 12 and 15 storey frames, the use of a 2mm thick steel plate shear wall is considered for all the models in this study. Table 2 summarizes the results from the static analyses of the three timber frames with 2mm SPSW. Table 2 also includes the geometric configurations of the three frames along with the dimensions of the timber beams and columns considered for the three frames.

Table 1 – Shear wall thickness parametric study

	No SPSW	0.5 mm SPSW	1mm SPSW	2mm SPSW	4mm SPSW
Bay Length (mm)	3500	3500	3500	3500	3500
Bay Width (mm)	5000	5000	5000	5000	5000
Storey Height (mm)	3200	3200	3200	3200	3200
Number of Storeys (mm)	9	9	9	9	9
Column Dimensions (mm)	215 x 266	215 x 266	215 x 266	215 x 266	215 x 266
Beam Dimensions (mm)	175 x 228	175 x 228	175 x 228	175 x 228	175 x 228
SPSW Thickness (mm)	0	0.5	1	2	4
Equiv. Brace Area (mm^2)	N/A	109.18	308.00	974.52	3383.14
Top Storey Drift (%)	5.10%	1.09%	0.75%	0.57%	0.48%

Numerical model of the hybrid SPSW-timber frame was developed OpenSees [21]. The prototype buildings in this study were discretized to only consider a single bay (as shown in Fig. 1) SPSW-timber frame via a 2D model. Elastic beam column elements with properties of 16c-E Douglas Fir Larch Glulam were selected for both beams and columns in the model. Different approaches for modeling SPSW are available in literature. Researchers have used detailed finite element models as well as strip models for representing the behaviour of steel SPSW structures. Thorburn et al. [11] introduced the concept of 'strip model' for modeling SPSW considering the post-buckling strength of the steel plate. Tromposch and Kulak [13] conducted large scale test to investigate the validity of the strip model and concluded that the strip model provides conservative estimates of both initial stiffness and ultimate capacity of SPSW. Continuum models such as those used by Elgaaly [22] and Driver et al. [10], has found to be acceptable accurate for modeling and capturing the response of SPSW. Recently, Webster [23] proposed a web plate strip model for SPSW. However, all the techniques were developed for steel frames with SPSW where the SPSW element is bounded by very stiff vertical and horizontal members. Chatterjee [24] proposed an equivalent braced model for modeling and analysing the seismic response of steel frames with SPSW. He developed two methods for calculating the equivalent brace for representing the SPSW in steel frame with and without considering the presence of stiff steel framing system. Since in this study the SPSW is used in timber frame, where the stiffness of timber frames is significantly smaller that the SPSW, the stiffness of the frame is not considered. Subsequently, the SPSW was modelled as a diagonal brace following the proposed equivalent stiffness methodology by Chatterjee [24]. Fig. 2 shows the schematic representation of the SPSW-timber frame in OpenSees. In this study all the beam column connections as well as the connection of the equivalent brace are considered to be rigid. Detailed finite element models using continuum models and experimental investigations are required to idealize the connection behaviour. Further studies are required to obtain the proper connection between the timber frame and SPSW.

Table 2 – Geometric configuration and static analysis results of three SPSW-Timber Frames

	2mm SPSW-Timber Frame		
	9 Storeys	12 Storeys	15 Storeys
Bay Length	3500	3500	3500
Bay Width	5000	5000	5000
Storey Height	3200	3200	3200
Number of Storeys	9	12	15
Column Dimensions (mm)	215 x 266	265 x 266	265 x 342
Beam Dimensions (mm)	175 x 228	175 x 228	175 x 228
SPSW Thickness	2	2	2
Equivalent Brace Area (mm^2)	974.5	974.5	974.5
Drift Percent	0.57%	0.68%	0.85%

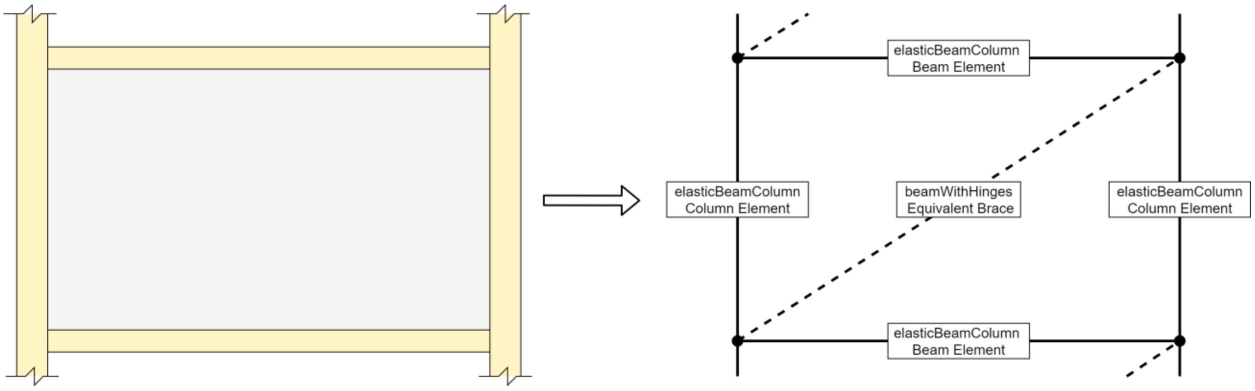

Fig. 2 – Hybrid moment frame discretization

6. Results from Numerical model

In order to investigate the performance of the three SPSW-timber frames, dynamic time history analyses were conducted using four ground motion records. The ground motions were selected from the PEER strong motion database [25]. The selected ground motions were scaled using SeismoMatch [26] to the design spectra of the prototype structures' location of Vancouver, BC. Ground motion data has been summarized in table 3.

Table 3 – Selected ground motion records

EQ No	**Earthquake**			**Recording Station Name**	**PGA_{max} (g)**	**PGV_{max} (cm/s.)**
	M	**Year**	**Name**			
1	7.3	1992	Landers	Yermo Fire Station	0.24	52
2	6.9	1989	Loma Prieta	Gilroy Array #3	0.56	36
3	6.5	1979	Imperial Valley	El Centro Array #11	0.36	34.44
4	7.6	1999	Chi-Chi, Taiwan	CHY101	0.35	71

Transient analysis was performed in OpenSees using the full duration of the scaled ground motions, and an additional 30 seconds of free vibration. Implementation of displacement recorders throughout the model's nodes and force recorders at the supports provided the required seismic performance data. In this study, the performance of the SPSW-timber frames was evaluated in-terms of maximum top storey drift, interstorey drift, and base shear. Fig. 3 summarizes the maximum top storey drift obtained from the time history analyses of the three SPSW-timber frames. It can be seen that the maximum top storey drift remains almost same for a particular SPSW-timber frame under the four considered ground motions.

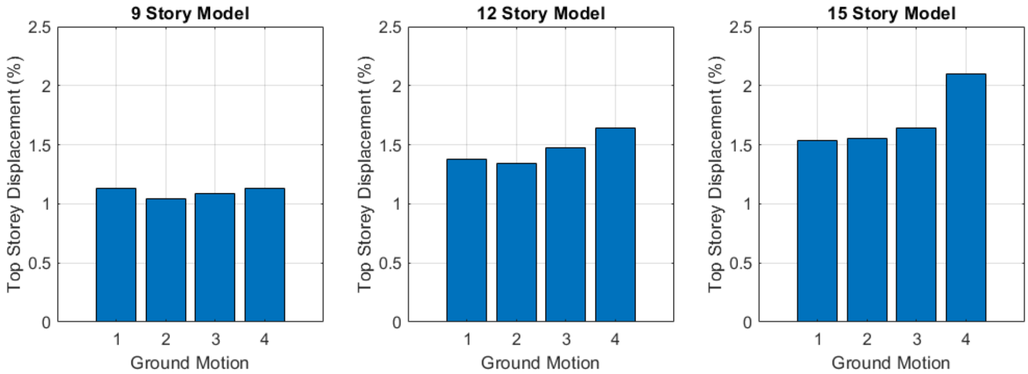

Fig. 3 – Maximum top storey displacement under selected time histories

Fig. 4 displays the interstorey drift of the three prototype models. Deflection and drift limits as specified in the National Building Code of Canada [20] limit interstory drift to 2.5% for normal importance buildings such as those explored in this study. In all cases modeled, interstory drifts were maintained within this limit; where the opportunity exists for more conservative design should a thicker steel plate be considered. From Fig. 4 it can be observed that for the 9 and 12 storey frames, the maximum interstorey drift occurred at storey 6. For the 15 storey frame, the maximum interstorey drift demand was recorded at storey 9.

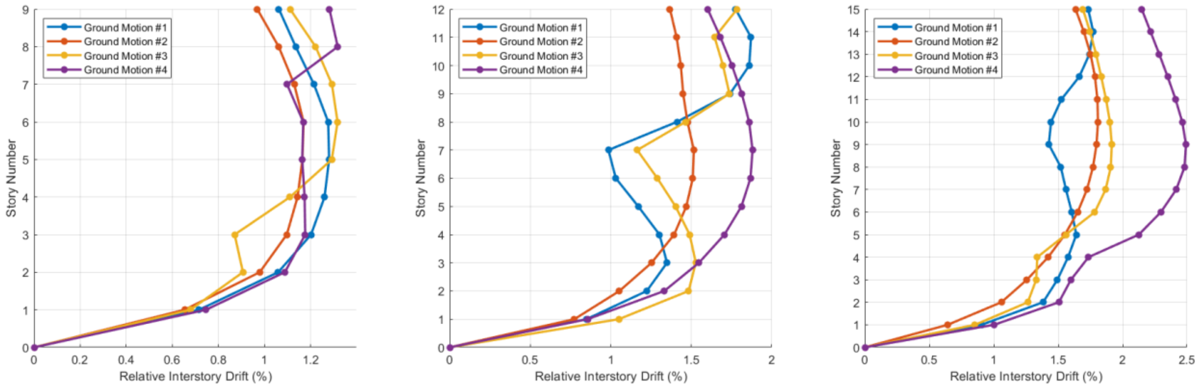

Fig. 4 – Relative interstory drift under selected time histories

Fig. 5 shows the maximum base shears observed under the selected ground motions for the prototype structures considered. From the base shears, it can be observed that the 12 and 15 story models have similar maximum base shears which can be attributed to the 15 story model having a longer period, albeit greater mass.

From the results of the three archetype frames, the following observation can be made:

- The maximum top storey drift demand remained same under all four ground motions for the 9 and 12 storey frames. However, for the 15 storey frame higher drift demand over 2% was observed.
- For the 9 storey frame, interstorey drift demands were comparable under four ground motions. However, for 12 and 15 storey frames, higher demands were observed under ground motion 4.
- For all three frames, the maximum base shear demand was below 600kN. However, under ground motion 3, the base shear demand in 12 storey frame reached 700kN.

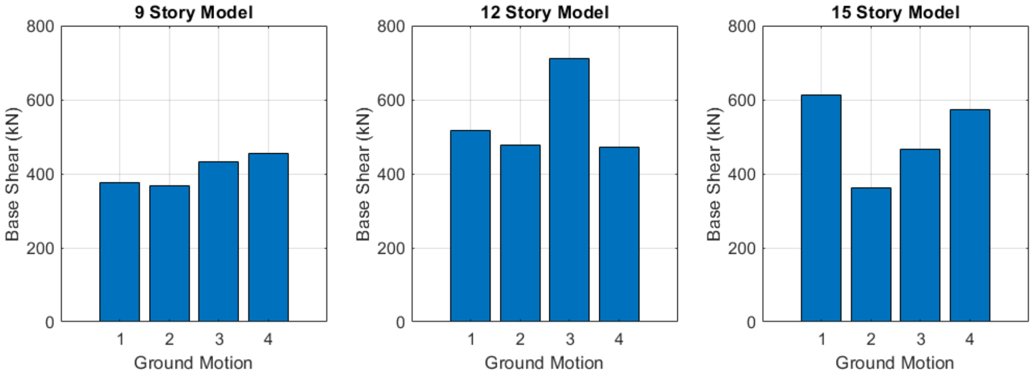

Fig. 5 – Maximum base shear under selected time histories

7. Conclusions

This study explored the feasibility of introducing a new hybrid system combining steel plate shear wall in timber frames. The results of the preliminary investigation look promising. Although the present study has its limitation in terms of detailed numerical model, connection between the timber frame and steel plate shear wall, and hysteretic response of the hybrid system under cyclic loading, this study will work as a benchmark for detailed future study. The authors are currently developing detailed finite element modeling in ABAQUS to investigate the response of the hybrid SPSW-timber frame under cyclic loading. Future studies will involve small scale testing of the proposed hybrid system, identifying the appropriate connection between the SPSW and timber frame, numerical modeling of the connection systems, and simplified design guidelines. Based on this exploratory numerical study, the following conclusions can be drawn:

- It is possible to achieve reasonable seismic performance with 2mm SPSW in combination with timber frames designed for gravity only.
- The proposed SPSW-timber frame structural system holds potential to be considered as an efficient system for high-rise timber construction.
- The proposed hybrid system was able to meet the lateral drift requirements outlined in the National Building Code of Canada.
- 15 storey timber frames can be reasonably constructed with the proposed system. With careful investigation and rigorous analysis, this limit can be further extended.

8. Acknowledgements

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