International Journal of Engineering &Technology, 8 (4) (2019) 433-443

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Steel framed structures with cross laminated timber infill shear walls and semi-rigid connections

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Abstract

In recent years, hybrid steel-timber structures are seeing an increasing use in modern building construction at a competitive price. Cross-laminated timber (CLT) is a prefabricated multi-layer engineered panel wood product, manufactured by gluing layers of solid-sawn lumber at perpendicular angles. Their orientation results in excellent structural rigidity in both orthogonal directions. CLT construction materials are used not only for flooring systems and roof assemblies, but CLT infill shear walls are also gaining a lot of interest as a promising alternative for sustainable primary lateral load resistance systems. This paper extends the current research background on hybrid steel-timber structures. To achieve that, this work is conducted in such way as to explore the potentiality of incorporating CLT infill shear walls within steel framed structures with semi-rigid connections (STSW). In particular, a three-dimensional finite element model using the general-purpose finite ele-ment program ANSYS is generated herein to study the mechanical behaviour of a single-bay, two storey STSW system with semi-rigid connections. Analytical results show that the presence of CLT infill shear walls can significantly improve the performance of moment-resisting frame systems, for multi-storey buildings. Moreover, it is observed from the extended parametrical study that the STSW systems show better performance when an appropriate plastic moment ratio index is defined.

Keywords: *Hybrid Steel-Timber Structures; CLT Infill Walls; Steel Moment Frames; Semi-Rigid Connections; Capacity Design; FEM.*

1. Introduction

Encompassing the beneficial properties of steel frames and Cross-laminated timber (CLT) shear walls, new innovative hybrid techniques can be developed for economical lateral load resisting systems. Among these, the steel frame with CLT infill shear walls and semi-rigid connections, namely STSW, (Figure 1), could provide a promising solution for new buildings with sustainable design considerations. CLT provides high tensile strength parallel to the grain and high compressive strength perpendicular to the grain of timber.

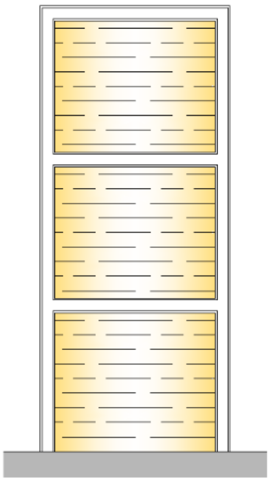


Fig. 1: Steel Frame with Cross-Laminated Timber Infill Shear Wall - STSW.

CLT is a sustainable solid-wood based construction material characterized by low mass, high stiffness, good seismic behaviour, and good thermal properties [1]. A wide range of different timber species for CLT production has been investigated as reported in the literature review [2]. Due to its advantages and the high level of prefabrication, CLT becomes a preferred and competitive construction material for modern buildings with sustainable design.

Limited studies have been reported on steel framed structures with CLT shear walls in recent decades. The available research focuses on the mechanical behaviour of CLT panels using experimental tests. Although analytical studies are an effective means to study the three-dimensional behaviour of those systems [3], [4], the available research within the international literature is scarce. STSW finite element (FE) modelling is considered a challenging task due to the high level of indeterminacies involved.

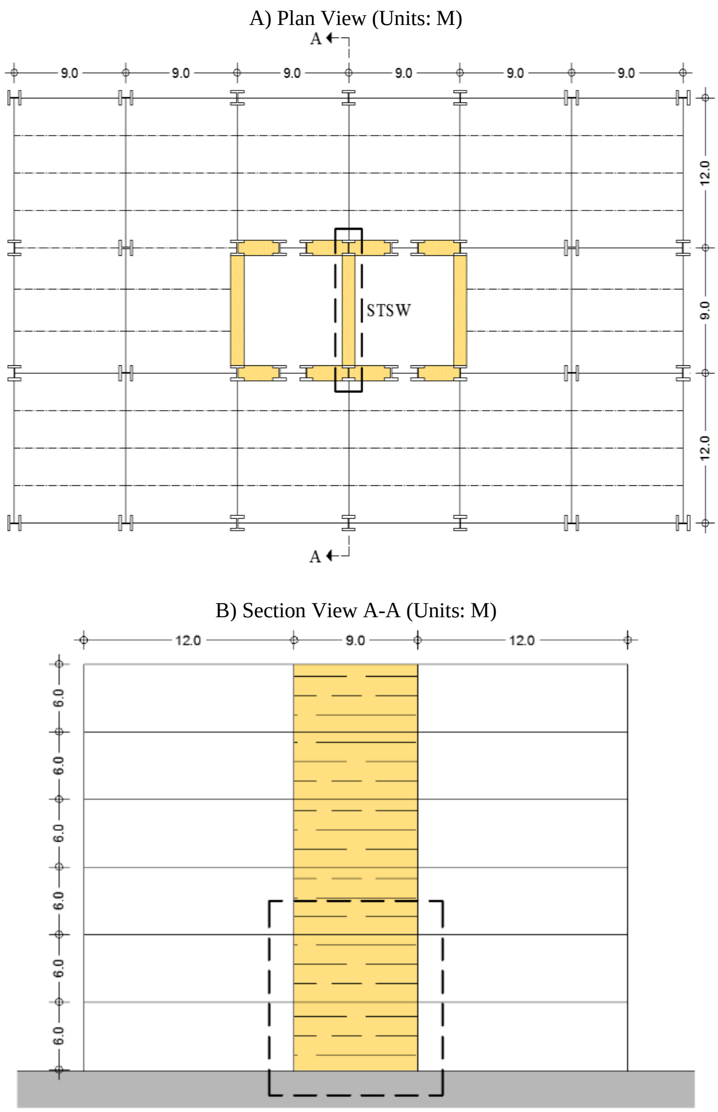
The main objective of this study is to explore the STSW system structural performance under combined in-plane and gravity loading, and to evaluate the effectiveness of the plastic moment ratio index, in the design of STSW systems. Other objectives of this work are to investigate the influence of cross-laminated timber infill shear walls on the response of steel framed structures with semi-rigid connections, and to compare the behaviour of the STSW system with similar composite steel – concrete structural systems from the literature. To achieve those objectives, three-dimensional models are developed and a number of STSW systems are numerically analyzed for various steel qualities for the vertical boundary elements (VBEs) and the horizontal boundary elements (HBE).

2. Methodology

This work is based on the numerical models developed to predict the nonlinear behaviour of composite steel-concrete structural systems consisted of steel frames with semi-rigid connections and reinforced concrete infill walls by Vogiatzis and Avdelas [5], [6], [7], and the experimental work conducted by Tong and his co-workers [8], [9]. Therefore, the same steel moment frame as used in [8], [9], and numerically modelled in [5], [6], [7], was further designed and modelled as a hybrid STSW system with semi-rigid connections.

2.1. Design considerations

The prototype six-storey building with core walls surrounded by steel frames was designed for hybrid wall systems in [8]. The plan and section view of the structure, are presented in Figure 2a and 2b. It can be seen that the core walls are concentrated at the center of the building. Steel frame systems are used to resist the gravity forces, and each floor system can serve as a collector for the core walls. The building was designed to be in seismic area 7 [10], according to the Equivalent Lateral Force Procedure [11]. The values for the acceleration coefficient, the velocity coefficient and the response modification factor are $A_\alpha = 0.4$, $A_v=0.4$ and $R = 5.5$, respectively. The seismic forces over the prototype six-storey building height and the corresponding shear diagram are given in Figure 2c.



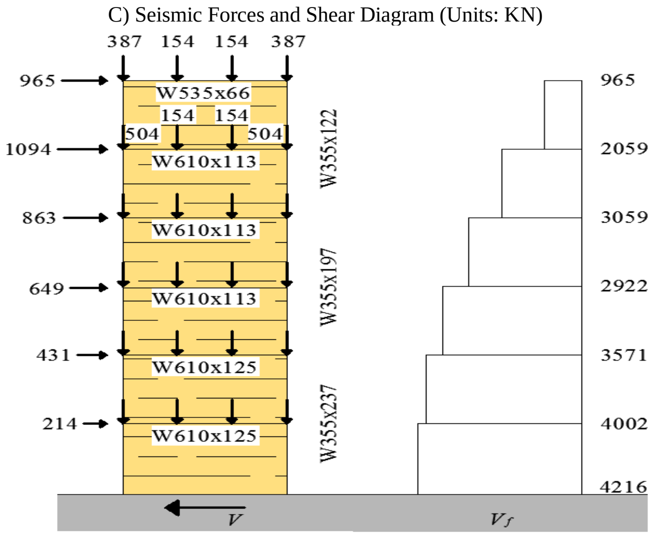


Fig. 2: Prototype Six-Storey Building.

2.2. Finite element analysis

2.2.1. General descriptions

Full three-dimensional finite element (FE) models were generated using the ANSYS software [12], based on the numerical methods developed in [5], [6], [7]. The loading process was controlled by displacement at the top beam up to a target drift at the end of the linear elastic phase of the CLT shear wall. Material characteristics and geometrical non-linearities, were included in the FE model.

2.2.2. Hybrid steel frame with CLT infill shear walls

The configuration of the STSW system investigated within this study is presented in Figure 3. For the infill shear walls, 3-ply CLT panels made of Canadian Hemlock [13] and characterized by inner and outer layer thicknesses of 40 mm and 30 mm respectively, have been adopted. Furthermore, for construction and stress concentration purposes, a circular cut off with a radius of 200 mm was applied in the corners of the cross-laminated timber infill shear walls.

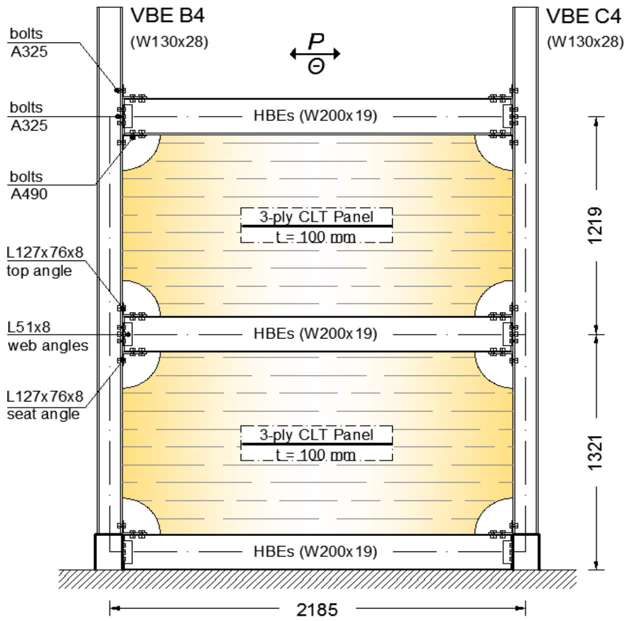


Fig. 3: Configuration of the STSW System with Semi-Rigid Connections.

2.2.3. Material modelling

The steel frame with semi-rigid connections numerical model was constructed using the higher order 3-D twenty node SOLID186 element. The material mechanical properties of each steel element are provided in Table 1. The characteristics of the numerical steel frame with semi-rigid connections are discussed in detail in [5], [8].

Table 1: Mechanical Properties of Steel Elements (Units: MPA)

Member	f_s	E_s	Member	f_s	E_s
VBEs	312	200,000	Web angles	282	200,000
HBEs	353	200,000	A325 Bolts	634	200,000
TS Angles	364	200,000	A490 Bolts	779	200,000

For the CLT infill walls, 3-D twenty node SOLID45 elements were utilised so as to simulate the orthotropic performance of the hemlock. Each layer of the CLT panel was given its own characteristics according to the lumber grain direction, Table 2. The shear modulus was generated from the CLT handbook [14], and the input Poisson's ratios from Canadian Lumber Properties [15].

Table 2: Mechanical Properties of the Canadian Hemlock Lumber

Properties	Parallel-to-grain direction (MPa)	Perpendicular-to-grain direction (MPa)
Stiffness	10,766.50	978.80
Compressive Strength	26.10	6.60
Tensile Strength	25.18	6.60

3. Numerical results

The response for the developed numerical model of the steel frame with CLT infill shear walls (STSW) system is shown in Figures 4 and 5. Although there are available procedures for CLT bending stiffness defined in EN 408 [16] and Eurocode 5 [17], in this work the drift limit for the STSW analysis, is assumed to reach the end of the linear elastic phase at a CLT shear strength target value $\bar{\tau}_{\text{lim}}$ of 4.00 MPa. The same conservative value was used by Stazi et al. [18], for the numerical analysis of reinforced concrete frames incorporated with CLT shear walls. The shear strength is related to the core zone of the panel. The panel core zone is defined by Frocht [19] and described for CLT infill shear walls in [18]. The CLT panel mean shear stress $\bar{\tau}$ can be obtained by:

$$\bar{\tau} = \frac{\text{F}}{\sqrt{2}\text{ta}} \tag{1}$$

The mean shear stress $\bar{\tau}$ is a function of the applied load F, the total thickness t and the side length α of the CLT infill shear walls. With reference to Andreolli et al. [20], the average shear stress value $\bar{\tau}_{\text{core}}$ in the core zone can be generated by Equation 2, below:

$$\bar{\tau}_{\text{core}} = 1.429 \cdot \bar{\tau} \tag{2}$$

Moreover, the maximum core zone shear stress value $\bar{\tau}_{\text{core,max}}$ can be extracted from Equation 3.

$$\bar{\tau}_{\text{core,max}} = 1.429 \cdot \bar{\tau}_{\text{max}} \tag{3}$$

It is assumed for this study that the end of the linear elastic phase will be at a target drift of 0.33% (8.72 mm). It can be observed from Table 3 and Figure 5d that for this target drift value, the shear strength of the numerical STSW is lower than the limit of 4.00 MPa.

Table 3: Theoretical and Numerical Shear Strength Results (Units: MPa)

Drift (%)	$\bar{\tau}_{\text{core}}$	$\bar{\tau}_{\text{core,max}}$	$\bar{\tau}_{\text{FEM}}$	$\bar{\tau}_{\text{FEM}}/\bar{\tau}_{\text{lim}}$
0.46	2.97	4.24	5.42	1.36
0.38	2.51	3.58	4.57	1.14
0.33	2.18	3.12	3.95	0.99

The effect of the CLT infill shear wall in the lateral response of the steel frame with semi-rigid connections is depicted in Figure 5. Within this comparison graph the data from a similar composite steel-concrete structural system as taken from [8], along with the scaled design lateral force for the bottom two stories of the prototype building as given in [9], are also included.

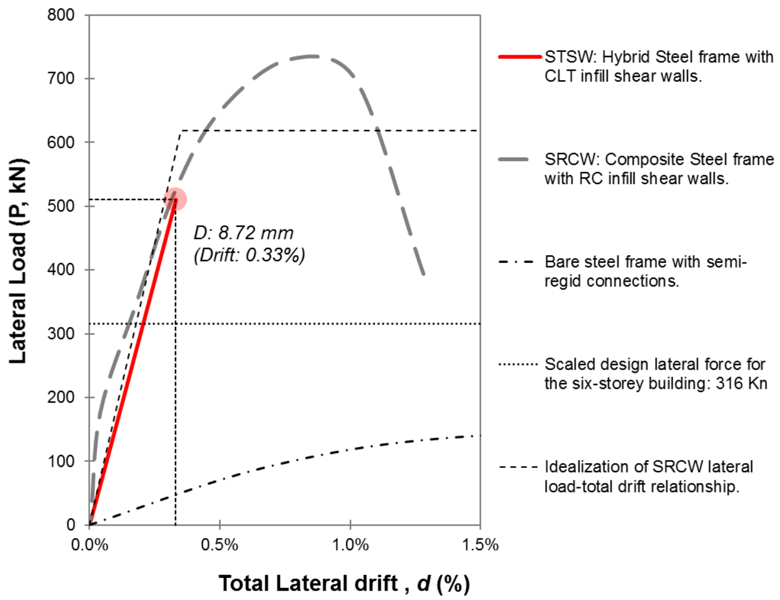
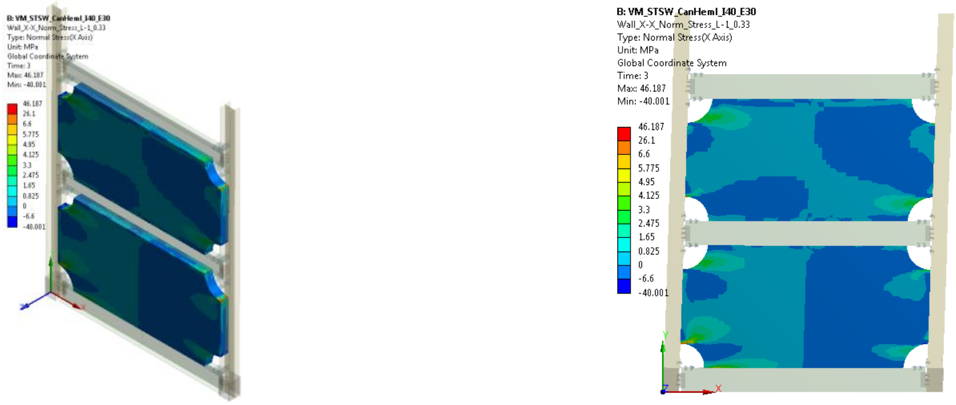


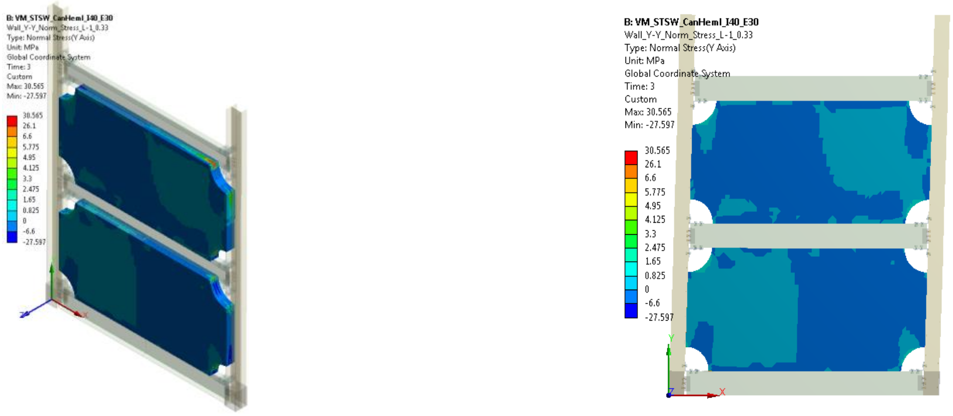
Fig. 4: Lateral Load - Total Drift Numerical Results of the STSW System.

A) Stress Values Parallel to the Fibers of the External Boards (Σ_x).



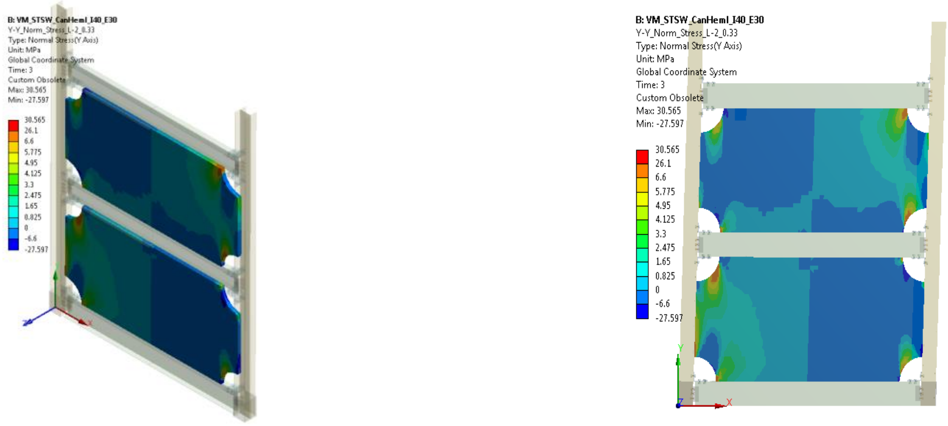
Side View **Section View**

B) Stress Values Perpendicular to the Fibers of the External Boards (Σ_y).



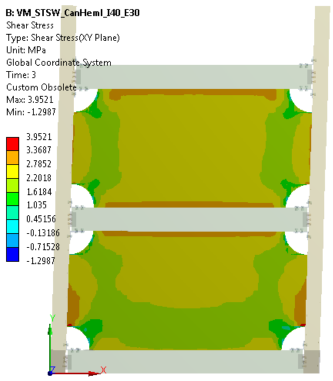
Side View **Section View**

C) Stress Values Perpendicular to the Fibers of the Internal Boards (Σ_y).



Side View **Section View**

D) Tangential Stress Values for the CLTS Infill Shear Wall (T_{xy}).



E) Von Mises Stress Values for the Bare Steel Moment Frame (Σ_o).

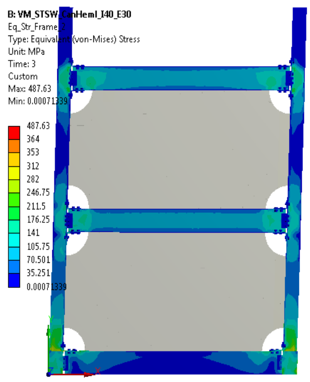


Fig. 5: FE-VM – Stress Results at the End of the Linear Phase.

4. Parametrical study

A parametric study is conducted here using the steel frame with CLT infill shear walls (STSW), finite element model. The main objective of this study is to investigate any advantage on using different steel quality for the horizontal boundary elements (HBEs) and the vertical boundary elements (VBEs). To this end, the method used in [5], for composite steel moment frames with reinforced concrete infill walls (SRCWs) will be applied here for STSW systems.

$$M_{pl} = W_{pl} \cdot f_{sy} = A_C \cdot d_C \cdot f_{sy} + A_T \cdot d_T \cdot f_{sy} \quad (4)$$

Using the steel material strength f_{sy}, the plastic moment values M_{pl} for the VBEs and HBEs of the STSW are calculated according to Equation 4. Where: W_{pl} is the plastic section modulus, A_C is the area in tension, A_T is the area in compression, d_C and d_T are the distances from the centroid of the area of the section in compression and tension respectively to the plastic neutral axis, measured perpendicular to the given principal axis.

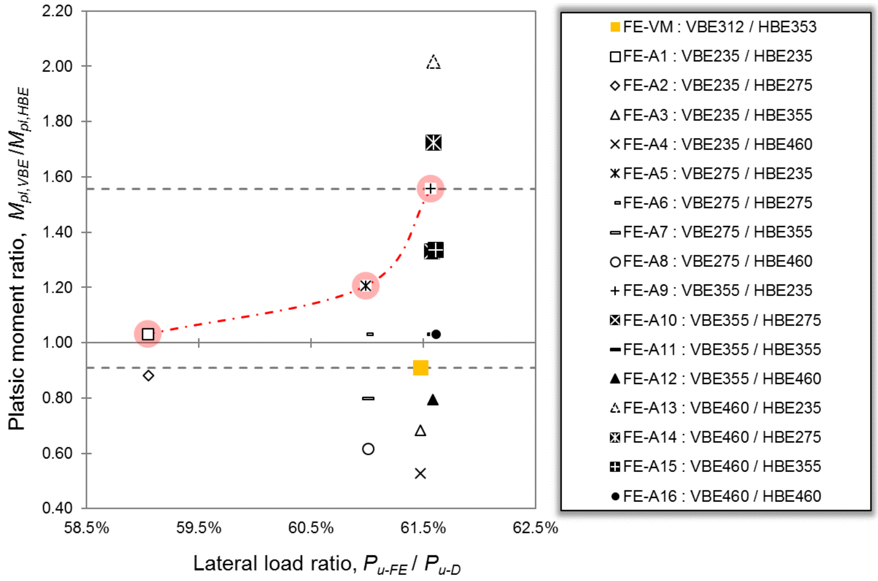


Fig. 6: Plastic Moment Ratio - Lateral Load Ratio.

In total 16 hybrid STSW systems have been analysed. The numerical specimens have been divided into four groups. Each group contains four numerical specimens with steel quality constant for the VBEs and varied for the HBEs. The steel qualities used are S235, S275 and S355. For comparison purposes the steel high strength quality S460 was also included. The graphical comparison results for the numerical STSW specimens are presented in Figure 6 for the plastic moment ratio against the lateral load ratio indexes, and in Figure 7 for the shear strength ratio against the lateral load ratio indexes. The stress values for σ_x, σ_y and τ_{xy} for the CLT infill shear walls along with von Mises stress distribution for the bare frame are presented from Figures 8 to 10, for selected STSWs (Figure 6).

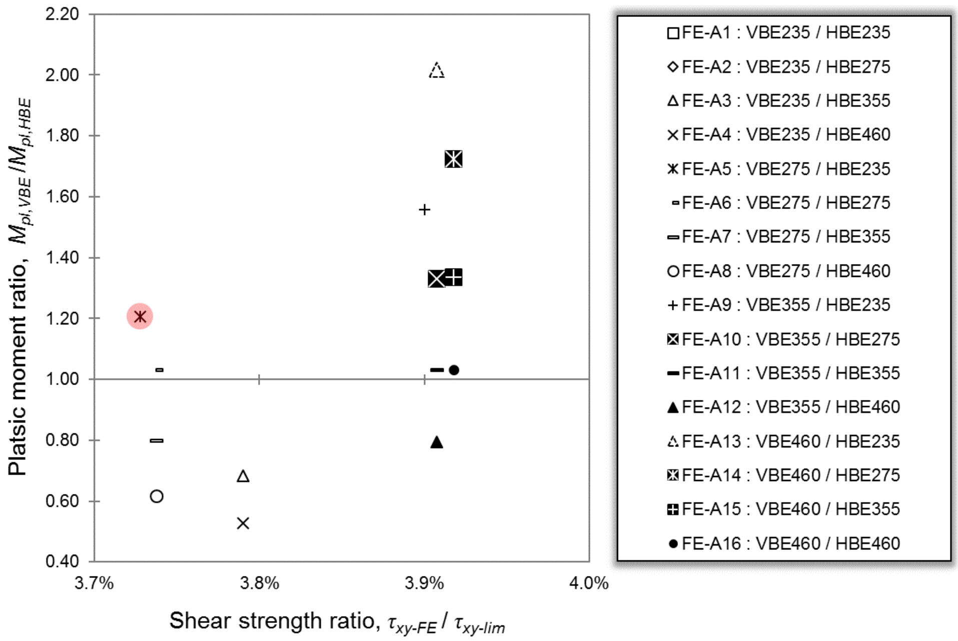
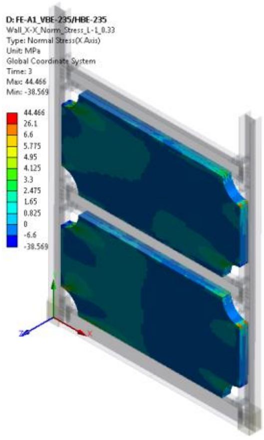
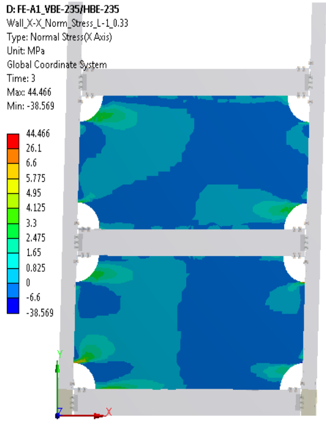


Fig. 7: Shear Strength Ratio - Lateral Load Ratio.

A) Stress Values Parallel to the Fibers of the External Boards (Σ_x).

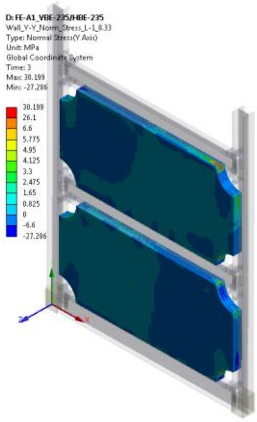


Side View



Section View

B) Stress Values Perpendicular to the Fibers of the External Boards (Σ_y).



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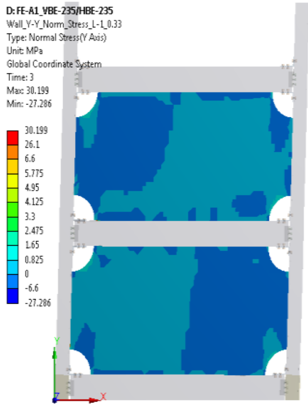
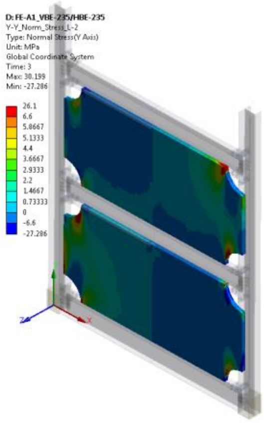


Section View

C) Stress Values Perpendicular to the Fibers of the Internal Boards (Σ_y).



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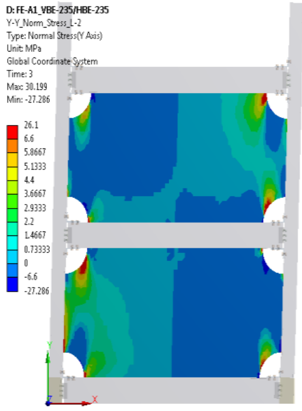
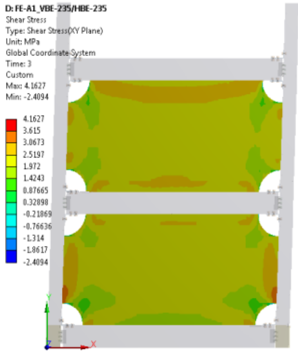


Section View

D) Tangential Stress Values for the CLT Infill Shear Walls (T_{xy}).



E) Von Mises Stress Values for the Bare Steel Moment Frame (Σ_o).

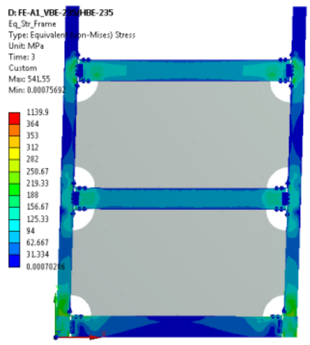
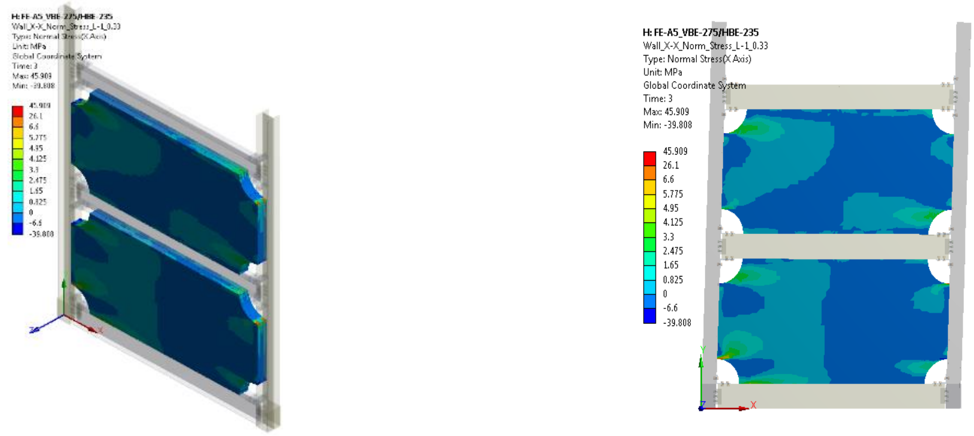


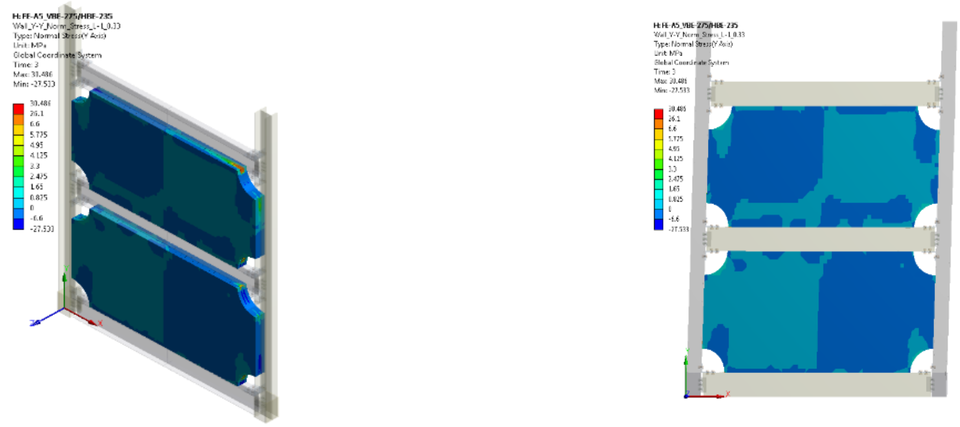
Fig. 8: FE-A1 – Stress Results at the End of the Linear Phase.

A) Stress Values Parallel to the Fibers of the External Boards (Σ_x).



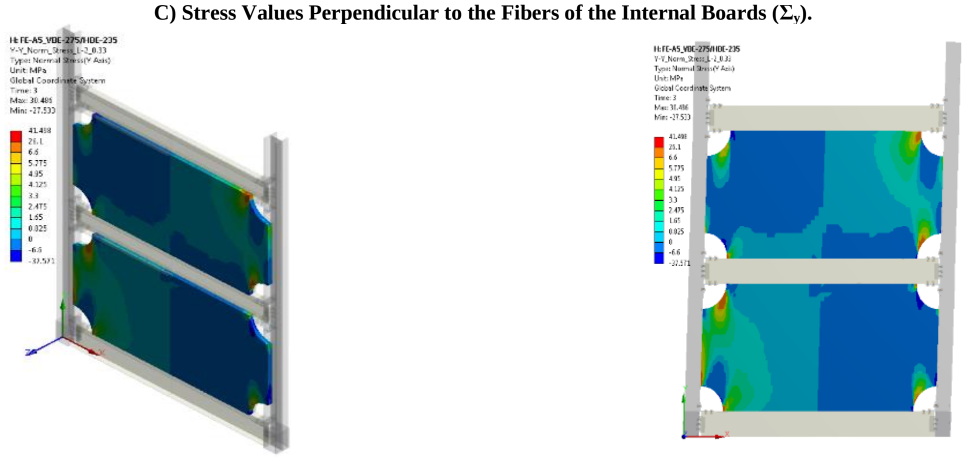
Side View Section View

B) Stress Values Perpendicular to the Fibers of the External Boards (Σ_y).



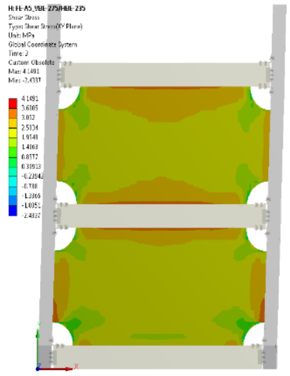
Side View Section View

C) Stress Values Perpendicular to the Fibers of the Internal Boards (Σ_y).



Side View Section View

D) Tangential Stress Values for the CLT Infill Shear Walls (T_{xy}).



E) Von Mises Stress Values for the Bare Steel Moment Frame (Σ_o).

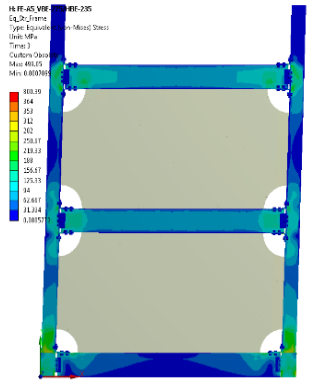
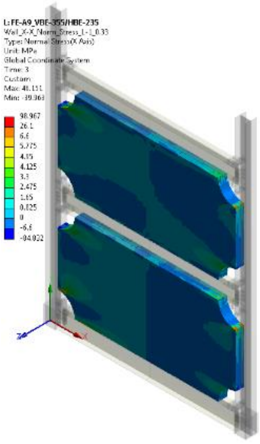
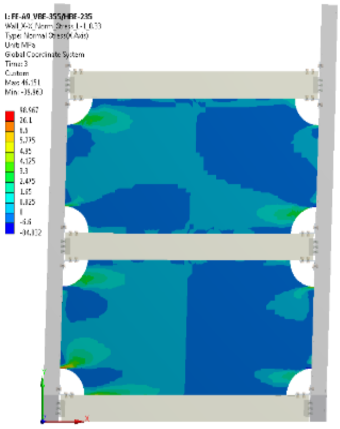


Fig. 9: FE-A5 – Stress Results At The End Of The Linear Phase.

A) Stress Values Parallel to the Fibers of the External Boards (Σ_x).

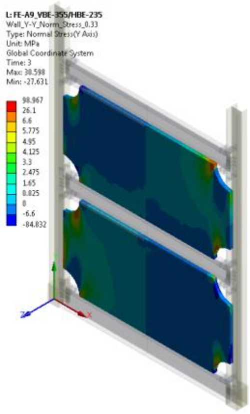


Side View



Section View

B) Stress Values Perpendicular to the Fibers of the External Boards (Σ_y).



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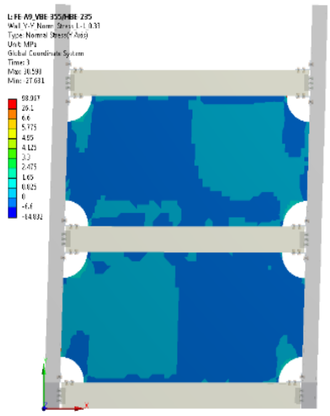
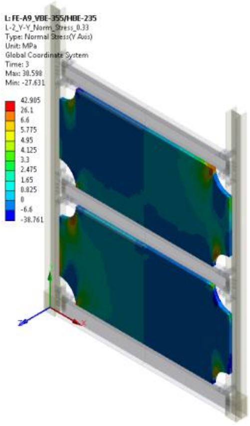


Section View

C) Stress Values Perpendicular to the Fibers of the Internal Boards (Σ_y).



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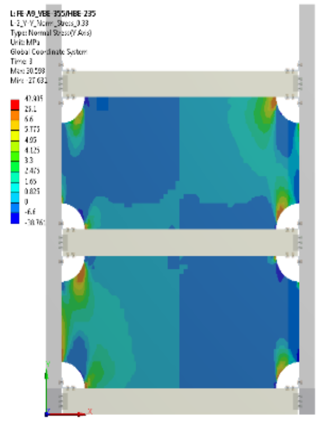
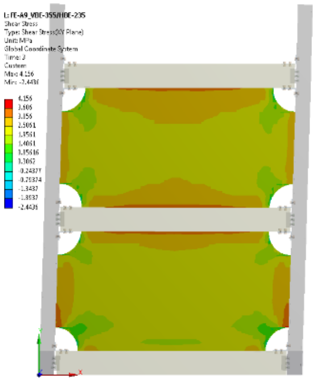


Section View

D) Tangential Stress Values for the CLT Infill Shear Walls (T_{xy}).



E) Von Mises Stress Values for the Bare Steel Moment Frame (Σ_o).

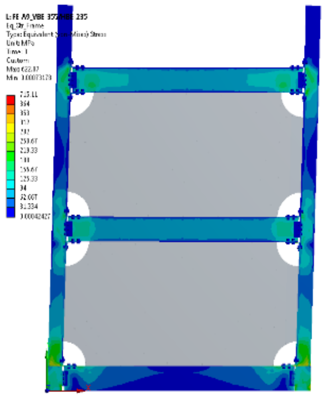


Fig. 10: FE-A9 – Stress Results at the End of the Linear Phase.

5. Discussion and conclusions

In the first part of this study the steel frame with CLT infill shear walls and semi-rigid connections was conceptually developed. Moreover, a detailed full scale three-dimensional finite element model was presented based on the computational design techniques generated in [5], [6]. The STSW model was simulated with the material properties of Canadian hemlock lumber for the CLT and was constructed in such a manner as to facilitate further parametric analyses, although the post elastic phase was not considered in this work. The numerical response of the STSW system has been reported in Figure 4 along with other curves related to a same steel frame with semi rigid connections [6], and a similar composite steel moment frame with reinforced concrete infill walls (SRCW) system [8], [9].
It was found that the STSW system (Figure 3) limit at the end of the linear phase (Figure 4) was at a drift of 0.33% (8.72 mm), indicating that this point is the beginning of the full yielding for the STSW. This limit has a close match with the drift point indicating the idealized yield strength for the SRCW system as this is given in [9]. Also, for a drift range up to 0.33%, the hybrid STSW system exhibits approximately the same stiffness with the composite SRCW.

The presence of the CLT infill wall alters significantly the performance of the bare steel frame with semi-rigid connections, by improving not only the lateral stiffness, but also the load capacity. The impact of this alteration is graphically observed within Figure 4.
The STSW numerical model has allowed, for the CLT infill shear wall, the normal stress values parallel to the fibers of the external boards σ_x (Figure 5a), and perpendicular to the fibers of the external boards σ_y, (Figure 5b). Furthermore, for the internal CLT boards, the normal stress values perpendicular to the fibers σ_y are also given (Figure 5c). Finally, the tangential stress values τ_{xy} (Figure 5d) for the CLT wall, are also included along with the von Mises stress values for the steel frame with semi-rigid connections (Figure 5e).
The obtained results unveil for the CLT infill shear wall, the formation of a diagonal compressive strut for stress values parallel to the fibers at the external boards (Figure 5a), and the formation of a diagonal tensile tie for stress values perpendicular to the fibers at the external boards (Figure 5b). This mechanism was also formed at the internal boards for stress values perpendicular to the fibers (Figure 5c). For the steel frame, no failure was recorded (Figure 5e).

In the second part of this work, a number of one bay, two-storey models were numerically analyzed in order to evaluate the effectiveness of the plastic moment ratio between the vertical and horizontal boundary elements (VBEs, HBEs) of the STSW system. The graphical comparison results in Figure 6 show that the STSW systems with semi-rigid connections are sensitive to the plastic moment ratio index. This can also be observed from the results of the selected models: FE-A1 (Figure 8), FE-A5 (Figure 9), FE-A9 (Figure 10). In contrast with the graphical comparison in Figure 7, the optimum design solution would be the STSW with steel qualities S275 and S235 for the VBEs and HBEs, respectively.

This study serves as a point of reference in order to advance the research towards the adoption of hybrid steel frames with cross-laminated timber infill shear walls and semi-rigid connections (STSW), as a lateral load resisting system for low to moderate seismicity areas. The STSW system appears to be an attractive solution for economical buildings with sustainable design. It appears that although some experimental studies can be found in [21], [22], the numerical investigation of STSW using three-dimensional finite element method is scarce. Furthermore, the STSW systems are not prescribed within Eurocode 8 [23]. On this basis it is necessary to undertake further experimental and numerical investigations, considering steel frame, CLT panels and connections characteristics, to better understand the flexural behaviour of the hybrid steel frame with CLT infill shear wall, STSW, as a lateral load resisting system.

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