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EXPERIMENTAL CHARACTERIZATION OF CLT SHEAR WALLS CONNECTED TO PERPENDICULAR WALLS

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ABSTRACT: "Box-type" CLT buildings are realized by connecting CLT panels through dowel-type fastener and mechanical anchor connections, which govern the lateral behaviour of these structures. However, while a lot of investigations in literature have been focused on the behaviour of connections placed at the base of CLT shear walls, typically hold downs and angle brackets, less studies have been focused on the behaviour of connections between perpendicular walls and how their affect the lateral response of CLT shear walls. This paper presents some results of a large experimental campaign aimed at investigating the effects of the interaction provided by perpendicular walls on the lateral behaviour of CLT shear walls. The findings of this experimental study showed that the structural interaction due to the presence of perpendicular wall significantly influence the lateral response of a CLT shear wall and increase its lateral performances, such as the lateral stiffness, the lateral capacity and the deformation capacity.

KEYWORDS: CLT shear wall, Perpendicular walls, Experimental tests, Lateral performance, Structural interaction.

1 INTRODUCTION

The Lateral Load Resisting System (LLRS) of Cross-Laminated Timber (CLT) buildings is composed of the CLT shear walls along with their base connections, which are typically realized using hold downs and angle brackets. Several testing programmes have been conducted to explore the lateral performance of CLT shear walls [1–3] and the results of these experimental investigations showed that the wall base connections govern the cyclic behaviour of a CLT shear wall system and provide the necessary ductility and energy dissipation. However, the lateral behaviour of a CLT shear wall is also influenced by other connections that can be found in the perimeter of the CLT panels. In particular, these connections vary depending on the type of construction. In this regard, CLT building construction typologies can be distinguished in "shear wall-type", in which the shear walls are not connected with the perpendicular walls in the corner of the building, and "box-type", in which the shear walls and the perpendicular walls are connected in the corner of the building by means of mechanical connections, see Figure 1.

The mechanical behaviour of CLT "box-type" buildings, especially those erected using the platform method, significantly depend on the effects of interactions between primary and secondary structural elements such as perpendicular walls, floor diaphragms, lintels and their mechanical connections, see for instance [4–9].

Concerning the "box-type" buildings, the influence of the perpendicular walls and the wall-to-wall connections is an issue of special interest. The effect of the interactions between the shear walls and the perpendicular walls on the lateral behaviour of CLT buildings was found in several numerical and experimental studies [10–13]. However, if from one side the effects of these interactions were found to be significative, from the other side no significant efforts were undertaken so far to investigate the effects of the interactions between CLT shear walls and perpendicular walls.

This paper presents an experimental campaign aimed at investigating the lateral response of CLT shear walls connected to perpendicular walls by means of typical screwed wall-to-wall connections. The main objective of this study is to quantify the increase of lateral performances of CLT shear walls as a result of their interactions with perpendicular walls.

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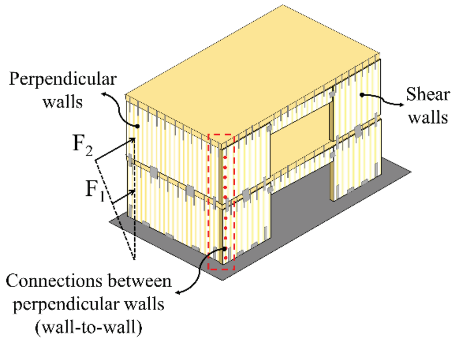


Figure 1: Representation of a "box-type" CLT building.

2 EXPERIMENTAL TEST PROGRAM

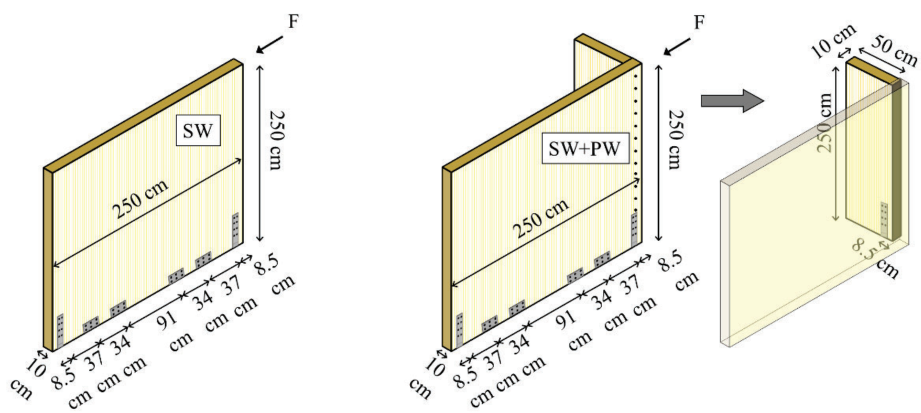
2.1 MATERIALS AND CONFIGURATIONS

The experimental tests presented in this study were carried out at L.E.D.A. Research Centre of the University of Enna "Kore" (Italy). CLT panels used during the tests consisted of five-layered panels with a total thickness equal to 100 mm and layer thicknesses of **20**-20-**20**-20-**20** mm (in bold the thickness of the layers arranged in the vertical direction). Hold-downs (HDs) type WHT340 [14] were used to anchor the wall panels against rocking displacements. These connectors were fastened in the vertical flange by means of twelve annular ringed nails 4×60 mm [15] and anchored to the foundation through one M16 bolt strength class 8.8. Whereas, angle brackets (ABs) type WBR90110 [14] were used to anchor the shear wall against sliding displacements. These connectors were fastened in the vertical flange by means of thirteen annular ringed nails 4×60 mm [15] and anchored to the foundation by means of two M12 bolts strength class 8.8. Self-tapping screws HBS 10×200 mm [16] were used to join the perpendicular wall with the shear wall. These connections, which were positioned to span across at least two layers of the perpendicular wall panel, were installed with a spacing of 250 mm, resulting in a total number of wall-to-wall connections equal to ten. Hold-downs, angle brackets and self-tapping screws were produced by Rothoblaas. In Figure 2 the connections used for the experimental tests are shown.

Two CLT wall assembly configurations were considered to investigate the lateral performance of CLT shear walls connected to CLT perpendicular walls: single Shear Wall configuration (SW), see Figure 3 (a), which considers a single CLT shear wall subjected to lateral load, and Shear Wall connected to a Perpendicular Wall configuration (SW+PW), see Figure 3 (b), which considers the same CLT shear wall subjected to lateral load connected to a perpendicular wall positioned at the end of the shear wall. All shear wall specimens were made of monolithic wall panels with dimensions equal to 250×250 cm. Each shear wall was anchored at base with two hold-downs located at the extremities of the wall panels and four angle brackets distributed along the shear wall length, see Figure 3 (a) and (b). Whereas, specimens of perpendicular walls consisted of monolithic wall panels with dimensions equal to 50×250 cm, each of which was anchored at the base with one hold-down, see Figure 3 (b).

a) b) c)

Figure 2: Connections used for the experimental tests:(a) hold-down WHT340, (b) Angle bracket WBR90110, (c) HBS 10×200 mm.



a) b)

Figure 3: CLT wall assembly configurations and geometries (measures in cm): (a) Single Shear Wall configuration (SW), (b) Shear Wall connected to a Perpendicular Wall configuration (SW+PW).

In total four experimental tests are presented in this study, including one monotonic and one cyclic test for each configuration. An overview of the experimental tests is given in Table 1.

Table 1: *Overview of the experimental tests*

ID test	Test type
SW_2.50	1 Monotonic
	1 Cyclic
SW+PW_2.50	1 Monotonic
	1 Cyclic

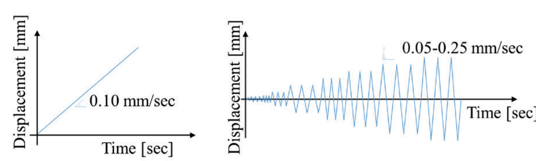
2.2 LOAD PROTOCOLS AND TEST SET UP

Monotonic tests were performed in displacement control with the imposed displacement increasing at a constant rate of 0.10 mm/sec, see Figure 4 (a), according to the standard procedure EN594 [17]. The cyclic tests were also performed in displacement control with a rate between 0.05 and 0.25 mm/sec, depending on the displacement level, according to the standard procedure in EN12512 [18], see Figure 4 (b). In order to study the lateral behaviour of the shear wall-perpendicular wall systems using fewer parameters, all tests were performed by applying the horizontal load without applying any vertical load.

The monotonic and the hysteretic parameters of the shear wall tests were evaluated according to EN12512 [18]. The mechanical parameters evaluated from the load-displacement curves of the monotonic tests are the yielding load F_y, yield displacement V_y, maximum load F_{max}, maximum displacement V_{max}, ultimate load F_{ult}, ultimate displacement V_{ult}, ductility D, and elastic stiffness K_{el}, which was calculated as the slope between 10% and 40% of the maximum load. The same parameters were assessed for backbone curves obtained from the cyclic tests, for both positive and negative displacements. The hysteretic parameters evaluated from the cyclic tests are the dissipated energy E_d, the equivalent viscous damping υ_{eq} and the normalised impairment of strength between the first and third cycles $\Delta F_{1\text{-}3}$.

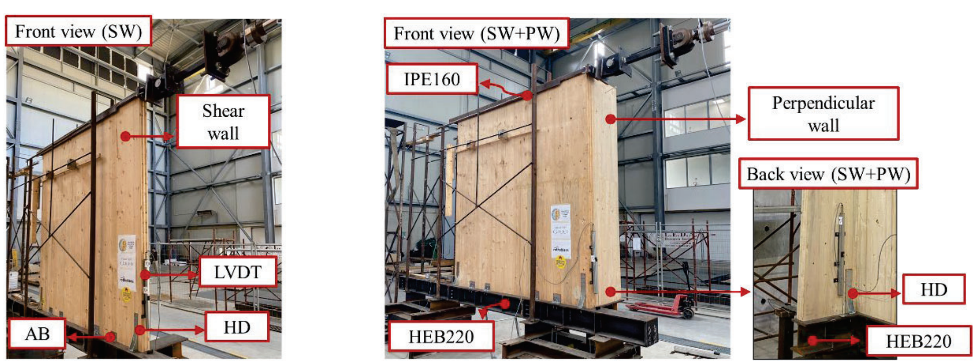
Figure 5 (a) and (b) shows photos of the test set-up for both SW_2.50 and SW+PW_2.50 configurations. The lateral load was applied by means of a 300 kN hydraulic actuator. In particular, the lateral load was distributed on the shear wall panel by means of a steel beam IPE 160 type, properly drilled and fastened to the top of the shear wall panel with 24 10×200 mm self-tapping screws. The CLT walls were anchored, through the hold-downs and the angle brackets described in the previous section, to two steel beams HEB 220 type, properly drilled, used to simulate the foundation (see Figure 5). Linear variable displacement transducers (LVDTs) were used to measure vertical and horizontal displacements at different locations of the specimens. Three LVDTs for measuring uplifts of shear wall and perpendicular wall were placed in lower corners of both shear wall and perpendicular wall. One LVDT was placed in the lower corner of the shear wall for measuring the horizontal base displacement. The horizontal head displacement of the shear wall was measured with an LVDT placed on an external steel structure, while another LVDT was used to monitor the horizontal displacement of the steel beam representing the foundation (HEB 220).

The horizontal displacement at the top of the shear wall was obtained by subtracting the horizontal displacement of the steel beam representing the foundation (HEB 220) from the horizontal displacement measured by the LVDT placed on the shear wall head. In order to avoid the out-of-plane movements of the CLT panels, a steel frame system was used.



a) b)

Figure 4: *Loading protocol for (a) monotonic and (b) cyclic tests.*



a) b)

Figure 5: *Photos of test set-up: a) SW configuration, b) SW+PW configuration.*

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3 EXPERIMENTAL RESULTS

Figure 6 (a) and (b) show some photos of the specimens at the end of the tests, for the two configurations SW_2.50 and SW+PW_2.50, respectively.

During the tests, the top lateral displacement of the systems was mainly governed by a combination of sliding and rocking mechanism with a predominant rocking. In particular, CLT panels behaved almost as rigid bodies and the deformations occurred in the joint between CLT panel and wall base connections.

As shown in Figure 7, deformations were observed at the base of the hold-downs (HDs) with failure mechanisms associated with the embedment of the wooden panel and failure of the nails of the vertical flange, with formation of plastic hinges. Moreover, some nails failed due to tearing of the nail head. As a result, the nail shank remained embedded in the CLT panel. Angle brackets (ABs) were capable of bearing both shear and tensile loads, but failures were observed in some instances in the nails of the vertical flange, resulting in the formation of plastic hinges. In some cases, failures were observed in both nails and bolts, see Figure 7. No failure was observed in the screws of the wall-to-wall connections.

A comparison between the hysteresis loops acquired from the cyclic tests and the load-displacement curves obtained from the monotonic tests for two test configurations, SW_2.50 and SW+PW_2.50, is shown in Figure 8 (a) and (b), respectively. Figure 8 (a) and (b) depict graphs indicating that the outcomes obtained from the cyclic test align with those from monotonic tests. From this figure, it can be observed the typical symmetrical hysteresis loops for positive and negative displacements in case of single shear wall configuration (SW).

a) b)

Figure 6: *Photos of the specimens at the end of the tests: a) SW_2.50, b) SW+PW_2.50.*

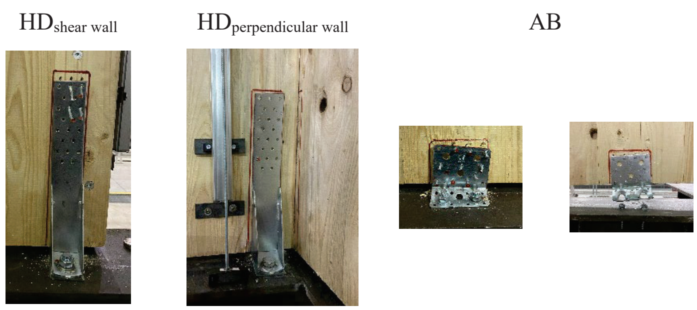
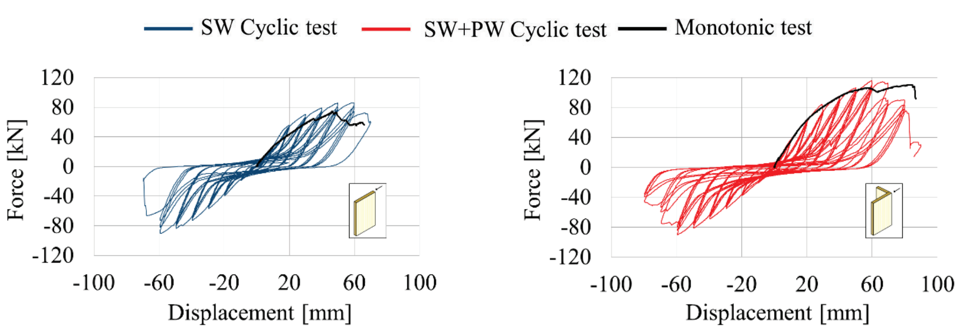


***Figure** 7*: *Some photos of the connection failures.*



a) b)

Figure 8: *Comparison between hysteresis loops and load-displacement-curves from monotonic tests: a) SW_2.50, b) SW+PW_2.50.*

On the other hand, for the SW+PW configuration, asymmetric hysteresis loops describe a different behaviour of the system for positive and negative displacements. This asymmetric behaviour is due to the asymmetric distribution of the base connections, when the perpendicular wall is taken into account.

Table 2 presents the mechanical parameters evaluated for the load-displacement curves obtained from the monotonic tests, while the mechanical parameters evaluated from the backbone curves of the cyclic tests are shown in Table 3, for both range of positive and negative displacements.

The findings from both monotonic and cyclic tests indicate that the structural interactions due to perpendicular wall contributes to improve the lateral performance of the shear wall. In the next, the percentage of the increments are calculated, considering the average values between the results obtained from the load-displacement curves of the SW test (both monotonic and cyclic tests in the range of positive displacements) and the results obtained from the load-displacement curves of the SW+PW tests (both monotonic and cyclic tests in the range of positive displacements).Specifically, the average increases of the lateral stiffness (K_{el}) and the lateral capacity (F_{max}) of the SW+PW configuration respect to the case of SW configuration, are about 40% and 41%, respectively. Moreover, results show an increment of the deformation capacity (V_{ult}) in case of SW+PW configuration equal to 25%.

Figure 9 shows the displacement paths, evaluated for both monotonic and cyclic tests, of the hold-down placed at the base of the shear wall and of the hold-down placed at the base of the perpendicular wall. The graphs plotted in Figure 9 show that hold downs of shear wall and perpendicular wall are subjected to close vertical displacements, due to the effect of the interaction provided by the wall-to-wall connections. Figure 9 highlights therefore that perpendicular walls may act as a hold-down system and have a significant effect on the behaviour of the lateral load resisting system. This can also be seen from the photo in Figure 9, which shows the uplifts of both shear wall and perpendicular wall.

The outcomes in terms of hysteretic parameters are shown in Figure 10 (a) and (b). Results of the equivalent viscous damping υ_{eq} and the normalised impairment of strength ΔF_{1-3} are plotted in graphs, which report in the horizontal axis the cycles and in the vertical axis the hysteretic parameters. The findings of cyclic tests show a maximum impairment of strength ΔF_{1-3} about 16.7% and 27.3% in case of SW and SW+PW configurations, respectively. Moreover, an average equivalent viscous damping υ_{eq} of 7.2% and 9.2% was found for the SW and SW+PW configuration, respectively.

The comparison of the dissipated energy E_d between SW and SW+PW configurations, is presented in Figure 10 (c). In both configurations the dissipated energy follows a similar trend for all tests. The maximum values of dissipated energy E_d were equal to 25 and 42 kJ, in case of SW and SW+PW configuration, respectively.

4 CONCLUSIONS

This paper presented an experimental campaign aimed at investigating the lateral response of CLT shear walls connected to perpendicular walls by means of typical screwed wall-to-wall connections. The lateral performance of two configurations was investigated: SW, i.e. single shear wall, and SW+PW, i.e. shear wall connected to perpendicular wall.

The purpose was to compare the results obtained from these two configurations in order to evaluate the increases in lateral performances of the shear wall when the perpendicular wall is taken into account. The results of this study show that shear walls connected to perpendicular walls reach significative higher structural performance in terms of lateral stiffness, lateral capacity and deformation capacity than typical single shear walls.

Table 2: *Mechanical parameters evaluated from the load-displacement curves of monotonic tests*

Test conf.	K_{el} [kN/mm]	F_y [kN]	F_{max} [kN]	F_{ult} [kN]	V_y [mm]	V_{max} [mm]	Vv_{ult} [mm]	D [-]
SW_2.50	2.28	67.67	74.46	59.57	28.03	46.41	64.00	2.38
SW+PW_2.50	3.19	91.69	110.19	88.16	27.66	83.84	86.81	3.14

Table 3*: Mechanical parameters evaluated from the backbone curves of the cyclic test*

Conf. test	Displ.	K_{el} [kN/mm]	F_y [kN]	F_{max} [kN]	F_{ult} [kN]	V_y [mm]	V_{max} [mm]	V_{ult} [mm]	D [-]
SW_2.50	(+)	2.4	79.6	85.9	69.9	33.2	49.9	69.9	2.1
	(-)	2.0	-85.1	-90.0	-72.0	-42.7	-59.4	-65.0	1.5
SW+PW_2.50	(+)	3.4	96.6	115.7	92.6	26.9	59.9	81.0	3.0
	(-)	1.9	-85.1	-90.1	-72.0	-42.7	-59.3	-75.0	1.7

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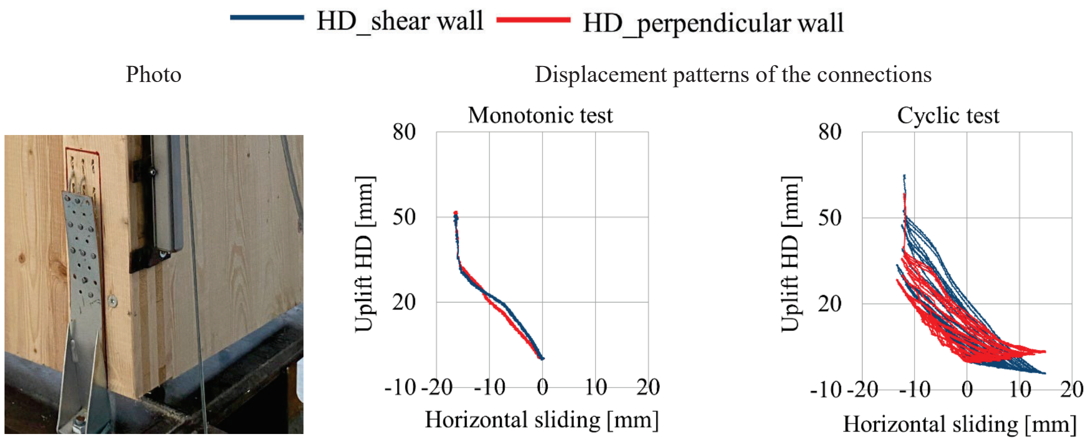

__Figure 9:__ Photos of the lower corner of the system and displacement path of the hold downs under tension.

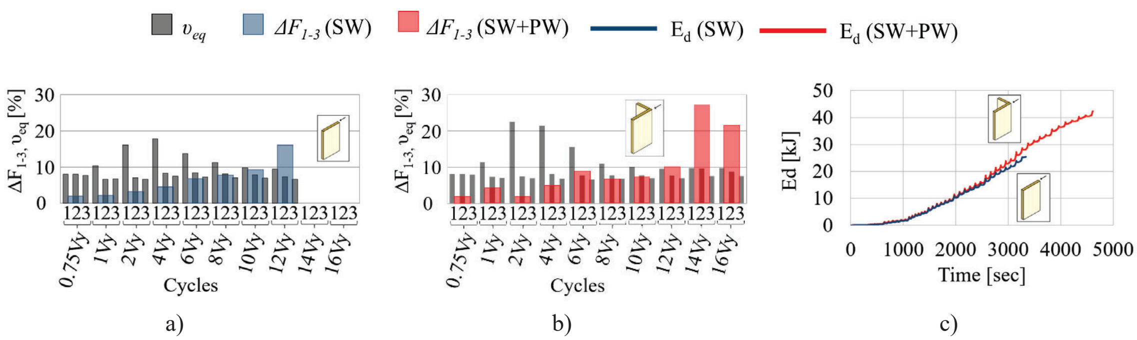

__Figure 10:__ a) Equivalent viscous damping υ_{eq} and the impairment of strength ΔF_{1-3} in case of SW configuration, b) equivalent viscous damping υ_{eq} and the impairment of strength ΔF_{1-3} in case of SW+PW configuration, c) comparison of dissipated energy E_d obtained from the cyclic tests of SW and SW+PW configurations.

Increase of performances is governed by the properties of the wall-to-wall connections as well as the properties of the hold downs used in the perpendicular walls. In this study, in which the same hold downs were used for anchoring the shear wall and the perpendicular wall, increase of lateral stiffness and lateral capacity up to 40% and 41% were found, respectively. Moreover, experimental results show an increment of the deformation capacity in case of SW+PW configuration equal to 25%.

The findings of this experimental study showed that the presence of perpendicular walls provide significative interaction effects with the shear walls, and contribute to the so-called box behaviour of CLT buildings. The results presented in this study provides valuable insights into the interaction between shear walls and perpendicular walls in CLT platform-type buildings, demonstrating that these interactions can significantly modify the lateral response of CLT structures.

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