1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.92

In-plane lateral testing of timber based shear walls and the influence of loading rate

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Abstract

In-plane lateral tests of timber based shear walls (e.g. light-frame or cross laminated timber walls) are the basis for the derivation of mechanical parameters required for the seismic and wind design (lateral load-bearing and displacement capacity, stiffness, ductility, etc.). The currently available testing standards, such as ISO 21581, do not provide explicit criteria for some testing parameters and boundary conditions, which are left to be decided upon with regard to the designated purpose of the tests. Racking tests can serve for evaluation of shear behaviour of the panels themselves or of the structural system as in actual conditions. In dependence of different aspect ratio and position in the structure (e.g. upper or lower building storey resulting in different vertical loads and boundary conditions), the behaviour of the panels can be mainly shear, rocking or combined shear-rocking. In the paper, the experience and conclusions of in-plane shear testing from various experimental campaigns conducted at the Slovenian National Building and Civil Engineering Institute are presented. Furthermore, the influence of the loading rate on the recently tested cyclic response of two variations of cross laminated timber wall systems is investigated. It was found and confirmed that the loading rate influences not only the lateral load-bearing capacity, but also the energy dissipation, which is crucial for seismic resistance of structures. The work is relevant for the purpose of understanding the influence of different test setup variations, panel and connections characteristics and loading protocols on the seismic response of timber shear walls. The research is therefore aimed towards a valid comparison of results from different testing campaigns and between different laboratories.

Key words: In-plane lateral testing, cross laminated timber, loading rate, test setup variation

1 Introduction

The number of timber structures for (residential) houses in Europe and worldwide is largely growing due to their sustainability potential (renewable resource), comfortable climate inside timber buildings, energy efficiency, fast erection and favourable cost-performance ratio. In order to understand the mechanical behaviour of timber based wall panels and their connections under in-plane lateral loading, monotonic and/or cyclic tests of walls are performed. These tests are crucial for design of timber shear wall structures on wind and seismic loading.

Results of numerous conducted experimental campaigns of different timber based shear walls can be found in literature (e.g. [1-3]). They focus on different issues; however, not many of them have studied the influence of the loading procedures for both monotonic and cyclic testing, the influence of boundary conditions and the post-processing of the results. Based on CUREE-Caltech Woodframe project, a testing protocol for force controlled quasi-static cyclic testing was investigated [4]. Gatto and Uang [5] have explored the effects of loading protocol on the performance of light-frame timber structures and found it has significant influence on the results. Lam et al [6] proved that different failure modes and ultimate strengths of shear walls are achieved under various test configurations and protocols. Adding vertical load to the light-frame timber shear wall did not prove to significantly alter the lateral capacity, stiffness or ductility [7, 8]. However, this is not the case for cross laminated timber (CLT) shear walls, where using higher vertical loads usually leads to higher horizontal load-carrying capacities and may change the behaviour of the specimens from flexural to shear [3, 9]. Dolan and Toothman [10] confirmed that the cyclic loading of shear walls yields reduced strength values compared to monotonic load. Dujić et al [11] applied three different cases of boundary conditions from real structures and changed the magnitude of vertical load. The boundary conditions influenced the load bearing capacity and response mechanisms.

The lack of the uniform standard for discussed testing was exposed already by Schädle and Blaß [9]. Currently, no uniform agreement about the application of realistic boundary conditions and load protocols for the cyclic loading exists in the international testing standards. Probably best-known standard for the monotonic testing of timber shear walls is EN 594 [12], while different standards include cyclic loading protocols; (i) EN 12512 [13] or ISO 16670 [14] for testing mechanical fasteners and (ii) ISO 21581 [15] or ASTM E2126 [16] for testing shear walls.

Standard ISO 21581 describes test methods for both static and cyclic shear tests of shear timber walls. The static test included in ISO 21581 is according to EN 594, while the cyclic displacement protocol is taken from ISO 16670. Depending on the purpose of the test, two methods of applying the boundary conditions are possible according to the code but not described fully in detail. One should induce shear failure of the wall while the other may reproduce the boundary conditions as in the actual structure and may result in failure of the connections. The current version of ISO 21581 does not fully

cover the post-processing/analysis of the results. For evaluation of some characteristics (besides the load-bearing and deformation capacity), such as ductility and energy dissipation, one has to rely on other standards (e.g. EN 12512) or research papers (e.g. [17]). It should be noted, for example, that ductility significantly influences the design of structures, but is highly dependent on the chosen criteria for its evaluation and can therefore be manipulated to best satisfy the purpose. There are also no specific values in ISO standards on the minimum number of specimens that need to be tested to obtain the reliable response of shear walls. ASTM E2126 on the other hand defines the number of tests with regard to their purpose; 2 if conducted for exploratory study and 3-5 for a specific specimen configuration if intended for code acceptance (required by the code evaluation agencies).
In the paper, the experience and conclusions of in-plane shear testing from various experimental campaigns conducted at the Slovenian National Building and Civil Engineering Institute are presented. Furthermore, the influence of the loading rate on the recently tested cyclic response of two variations of CLT wall systems was investigated.

2 Timber shear walls used in contemporary design

2.1 Light-frame panels

Light-frame timber structures have a history of about 150 years but are still commonly used with numerous variations of geometry, frame construction, sheathing materials and connections improvements. Several advantages are offered by conventional timber frame structures, such as flexibility in construction, low thermal conductivity of the wall, sustainability, etc. When subjected to seismic loads, the behaviour of timber frame structures is favourable due to their low weight and ductile behaviour [1]. The dissipative zones of light-frame walls are the connections between the sheathing and the framing as well as the hold-downs and angle brackets, whereas the timber members themselves can be regarded as behaving elastically.

2.2 Cross laminated timber (CLT)

Mass timber buildings are most commonly made of cross laminated timber panels, which are assembled from transverse timber laminations, either glued or connected by dowels or nails. The most spread solution in practice is glued CLT, since it is the most resistant to moisture induced deformations (due to cross-wise lamination swelling and shrinking are nearly prevented). The CLT shear walls are connected to the foundation or the CLT slab by hold-downs and angle brackets (using metal fasteners such as nails, screws and anchor bolts). When subjected to lateral loads, the CLT walls are exposed to rocking, sliding or combined movement. Looking at a single CLT wall, the dissipative zones are the connections at the top and bottom of the panel, whereas the panel itself remains in elastic state. If multi-panel wall solutions are used, also the vertical connections between the panels can be considered as the dissipation zones [3].

2.3 Other novel systems

In addition to CLT and timber frame walls, other systems incorporating timber or timber products are possible, such as timber-glass load-bearing panels, structural insulated panels (SIPs), CLT with special channels for installations (e.g. multifunctional CLT), various prefabricated timber wall elements (e.g. prefabricated timber "brick" elements in small units primarily using sawmill residues) and others. Each of the above listed systems has a unique mechanism of load transfer in the case of in-plane shear loading and consequently different location of dissipation zones.

3 In-plane shear testing

3.1 Test setup

Boundary conditions, vertical load

As already mentioned, the purpose of the experimental tests to some extent defines also the test setup and the testing boundary conditions, as well as the size of the specimens. The fixation of the tested panels at the bottom can either be overdesigned to clearly recognize the behaviour of the panels (as may be the case in light-frame timber panels) or as build in structures to evaluate the behaviour of the whole structural system. Similarly also the foundation can either be a steel or concrete foundation providing rigid support or a timber girder or slab which may increase the walls' lateral displacements in case of higher vertical loads due to the compressive deformation of the ground (e.g. compression perpendicular to the fibre of the CLT slab). At the top, rotation of the panel is commonly enabled, however it can also be fixed if more appropriate. To prevent the out-of-plane deformations or buckling out-of-plane supports must be provided.

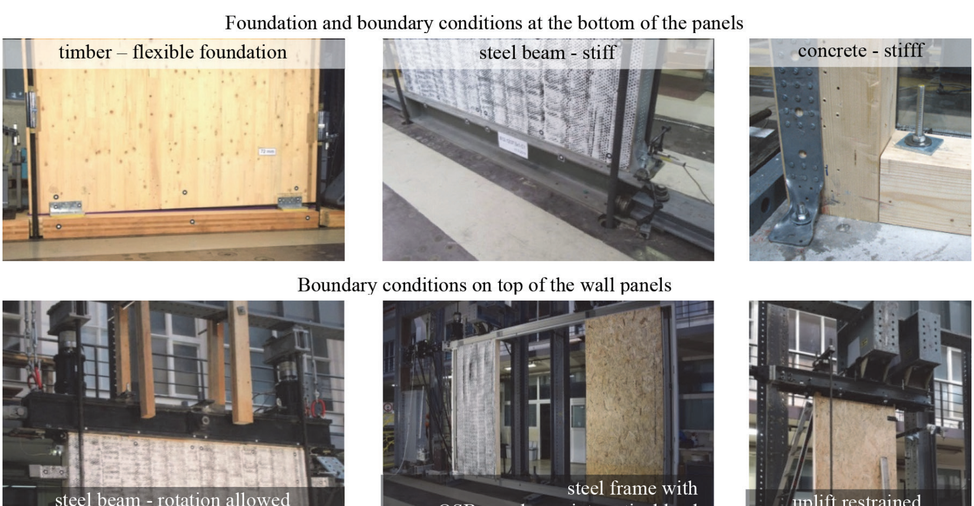


Figure 1. Some examples of various possible boundary conditions of timber shear wall experiments, Photo: Slovenian National Building and Civil Engineering Institute (ZAG Ljubljana)

The amount of vertical load may significantly influence the behaviour of the panels as it together with panel geometry characteristics (i.e. aspect ratio of the walls) and connections influences the failure mechanism [3]. The vertical load is usually applied as uniform load which may be achieved either with some special system for distribution of load or through a designed element, which due to its characteristics enables uniform transfer. In the setup below (Figure 2), designed to test CLT panels connected to CLT slab with special angle brackets, the vertical load was imposed through two vertical actuators through a steel girder.

Measuring equipment

Some standards, such as EN 594, have prescribed positions for measuring displacements, which are essential to evaluate the panels' behaviour. Nevertheless, besides lateral displacement at the top and at the bottom of the panel, also uplifts (and settlements) at both sides at the bottom of the panel are commonly measured. Depending on the aim of the investigation also other measuring positions can be set up. Specific linear variable differential transformers (LVDTs) may for example serve to control the loading protocol, which in cyclic tests enables symmetrical results in terms of interested displacements (may even be a difference or a sum of one or more LVDTs) in both directions of loading. In some cases of highly deformable panels also the measurement of the diagonal displacement is prescribed.
To provide even more information on the behaviour, an optical measurement system is often used. With digital image correlation (DIC) specific points of interest can be monitored in real time during the tests, while also the entire surface can be measured (both seen in Figure 3). The deformations obtained with the DIC can indicate the position of oncoming damage. They become very valuable also in case of difficulites with mechanical measuring equipment (e.g. limited range of measurement or space for set up, etc.).

Figure 2. Test setup for cyclic tests of CLT wall system

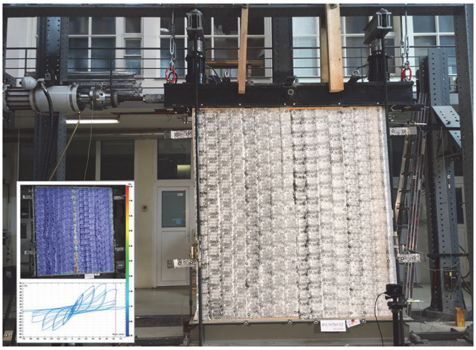


Figure 3. Test setup with an optical measurement system for cyclic tests of light-frame timber wall panels

3.2 Test protocols

The loading is commonly displacement controlled. The cyclic loading protocols differ in several aspects. Each increase of the amplitude displacement is defined according to the results of the monotonic tests; in some standards as a percentage of yield displacement (d_y) (ISO 21581, ISO 12512, Method A in ASTM E2126) while in others as a percentage of ultimate displacement (d_u) (ISO 16670, Method B in ASTM E2126). The ultimate displacement is defined as the first of: a) the displacement at failure, b) the displacement at 80 % of F_{max} in the descending part of the load-displacement curve (EN 594, ISO 21581 and EN 12512) or c) the displacement limit (H/15 in EN 594, where H is wall height; or 30 mm in EN 12512). Using ultimate displacement to define the amplitude displacements has its advantages, since the yield displacements are determined differently in the codes, if they are defined at all. Figure 4a shows a loading protocol provided in EN 12512, which was used for the test results presented further in the paper. It was determined on the basis of a previous monotonic test.

The loading protocols also differ in the number of cycles at both low and higher displacement amplitudes. In addition, the allowed ranges of loading rates also differ, although loading with constant cycle frequencies is also possible.

3.3 Evaluation of results

In order to best compare the test results in terms of resistance, deformation capacity, stiffness and ductility, the results need to be properly idealised. Figure 4b shows the idealisation according to EN 12512 with additional bi-linear idealisation considering the equivalent potential energy criterion (sometimes referred to as "Equivalent Energy Elastic-Plastic curve" ("EEEP") method). In EN 12512, the elastic stiffness k_{el} is evaluated as secant stiffness at 10 % and 40 % of F_{max} (displacements $d_{10\,\%}$ and $d_{40\,\%}$, respectively), while the plastic stiffness (k_{pl}) is determined as $1/6 \cdot k_{el}$. The idealised yield displacement (d_y) is determined as the intersection of the curve between 10 % and 40 % F_{max} (k_{el}) and the tangent to the hysteresis envelope curve with k_{pl} defining the slope (Figure 4b). The ultimate displacement (d_u) is according to this standard determined as the point, at which the post-peak resistance drops to 80 % of F_{max}.

The EEEP method is used by some researchers [17] and in standards (e.g. ASTM E2126-11) to idealize test results of timber shear walls or connections. It is also commonly used in the analysis of shear behaviour of other types of structural walls, since it adds a physics-based criterion to determine the elastic displacement of the bi-linear idealized curve. For its evaluation, either the effective stiffness (K_{ef}) or the idealised force (F_{id}) must be determined in addition to the ultimate displacement. For the determination of the bi-linear idealised curve in Figure 4b, K_{ef} is assumed according to EN 12512, while F_{id} and corresponding d_e are then calculated based on the EEEP. In contrast, ASTM E2126-11 assumes K_{ef} as secant stiffness at 40 % F_{max} and consequently provides different d_e

and F_{id}. Another commonly used idealisation procedure for results of shear tests on timber walls/connections is the Kawai and Yasumura idealisation [17].

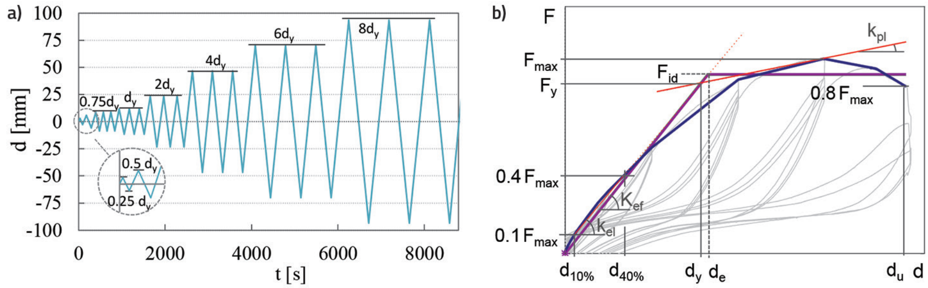


Figure 4. a) Time history loading protocol according to EN 12512, b) Idealisation according to EN 12512 and bi-linear curve determined considering equivalent energy criterion (EEEP method)

The definition of yield displacement is important because it determines the ductility μ (d_u/d_y). In Figure 4b it can be seen that the ductility is smaller when the yield displacement is considered as the elastic displacement (d_e) of the bi-linear curve (ductility d_u/d_e). In our experience, the equivalent energy criterion gives more conservative results compared to EN 12512 alone in terms of ductility (if the effective stiffness of the bi-linear curved is assumed as stiffness at d_y). It is also conservative in terms of resistance, since idealized shear resistances F_{id} are further compared.

In order to eliminate the differences in evaluation of test results of timber connections and walls, there are ongoing initiatives and activities to unify the standards for analysis of the results as well as to unify the loading protocols [18].

4. Influence of the loading rate on the behaviour of CLT shear walls

The possible loading rates prescribed in current standards for cyclic shear tests on timber joints or walls are quite broad (e.g. 0.02-0.2 mm in EN 12512, 0.1-10 mm in ISO 16670, 1-30 min in EN 21581). The cyclic shear tests can become very time consuming, if the prescribed lower limit rates are adopted. On the other hand, the tests are more difficult to control if the loading rate is too high. Since the range of possible loading rates is wide, our recent experimental campaign with CLT panels also investigated the effect of loading rate on the response of panels. The aim of the campaign was to investigate the behaviour of CLT panels (2490/2490/100 mm 3-layer) connected to CLT slabs with special insulated angle-bracket connections that can withstand both shear and tensile forces [19], as well as the influence of different sound insulation layers under the panels on the response. More detailed information about the entire experimental campaign and the results can be found in [20].

Two loading rates were used for two different wall systems, summarised in Table 1. Specimens labelled "W-Unin" were tested under low vertical load (10 kN/m), while specimens labelled "W-SR1200" had an additional polyurethane insulation layer (SR1200,

[20]) under the panel and were tested under higher vertical load (50 kN/m). All panels had two angle brackets positioned 400 mm from the edges on one side of the panel. For each specimen type, one test was performed at 0.5 mm/s and one at 10-times higher maximum loading rate (i.e. 5 mm/s, marked with "*").

Table 1. Summarised characteristics and results of tests of CLT walls with varied loading rate

Test	**Vertical load** [kN/m]	**Max. rate** [mm/s]	k_{el} [kN/mm]	F_y [kN]	d_y [mm]	F_{max} [kN]	d_{Fmax} [mm]	d_u [mm]	$\mu_{EN12512}$ [/]
W-Unin/1	10	0.5	2.05	47.7	23.7	56.2	48.2	80.4	3.50
W-Unin/2*	10	5.0	2.42	50.0	21.0	61.4	57.6	71.7	3.45
W-SR1200/1	50	0.5	4.07	66.9	15.6	93.9	65.0	93.7	6.04
W-SR1200/2*	50	5.0	3.64	72.8	19.1	101.0	73.2	83.4	4.40

The obtained hysteresis curves for the two specimens and boundary condition combinations tested under different loading rates are compared in Figure 5 in diagrams for lateral resistance – lateral displacement. The results clearly show that with higher loading rate, the load-bearing capacity is increased; an average increase of 8 % was obtained for the two test combinations when both loading directions are considered. On the other hand, there seems to be a decrease in deformation capacity with increased loading rate for both specimen variations, although the ultimate deformation for test W-SR1200/2* in negative loading direction was not reached. The ultimate displacement capacity decreased on average by 11 % with higher loading rate for the W-Unin specimen (Figure 5, left).

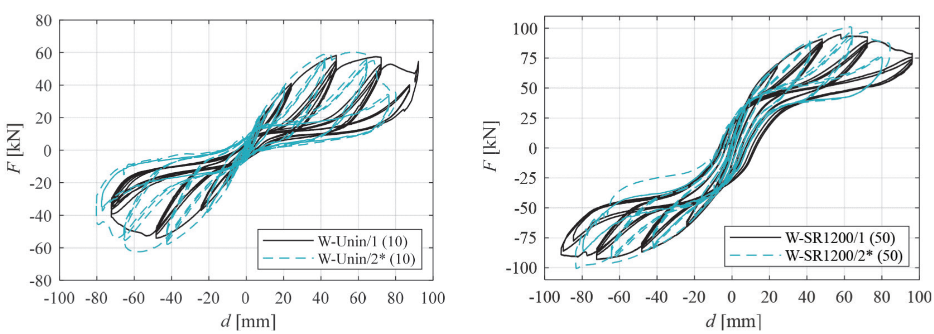


Figure 5. Comparison of lateral force - displacement hysteresis responses of uninsulated CLT wall systems under low vertical load tested with different loading rate

No systematic difference was found in the elastic stiffness and yielding displacements determined according to EN 12512. However, the analysis of energy dissipation in each cycle showed that with higher loading rate, the relative amount of dissipated energy compared to the input energy was also higher. The energy dissipation evaluated for the four tests in terms of equivalent viscous damping coefficient ν_{eq} according to EN 12512 for the 1st and 3rd loading cycle, is presented in Figure 6. In addition, Table 2 shows the lowest damping coefficient obtained for each test and the average values of the 1st and 3rd loading cycle up to (and including) the displacement amplitude at which F_{max} was reached.

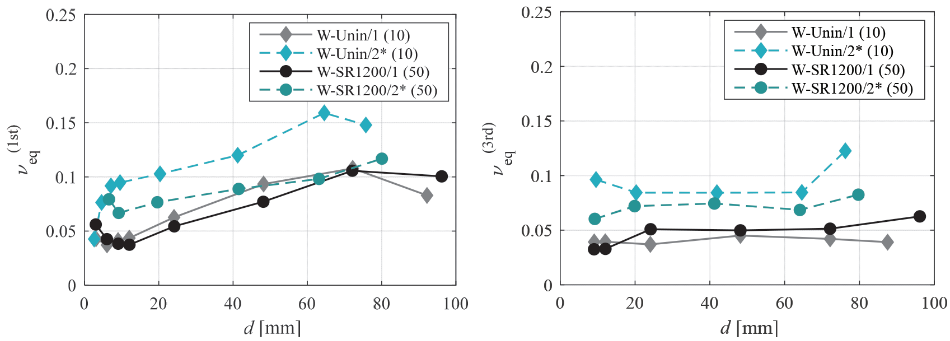
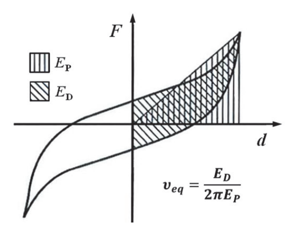


Figure 6. Equivalent viscous damping coefficients ν_{eq} obtained in 1st (left) and 3rd (right) loading cycles of the conducted tests.

Table 2. Minimum and mean equivalent viscous damping coefficient ν_{eq} for the 1st and 3rd loading cycles, determined for the conducted tests (with figure for its definition according to EN12512 on the right)

Test	**Vertical load** [kN/m]	**Max. rate** [mm/s]	$\nu_{eq,min}^{(1\text{-}3,all)}$ [%]	$\nu_{eq,ave}^{(1)}$ [%]	$\nu_{eq,ave}^{(3)}$ [%]	
W-Unin/1	10	0.5	3.7	5.3	4.0	
W-Unin/2*	10	5.0	4.3	8.7	8.8	
W-SR1200/1	50	0.5	3.3	5.9	4.4	
W-SR1200/2*	50	5.0	6.0	8.8	7.2	
Note: E_p – potential energy, E_d – dissipated energy						

It should be noted that at higher horizontal loading rate, there were difficulties in keeping the low vertical load constant due to the test set-up and equipment (10 kN/m vertical load, i.e. 25 kN on both actuators together). Therefore, if the vertical load is low, the horizontal loading rate should be adjusted to the actuators' control capabilities or use a different test setup, where the vertical load is applied by mechanical weights and not by the actuators.

5 Conclusions

Experiences and conclusions of in-plane shear experiments from various campaigns are presented to understand the influence of different test setups, panel and connection properties, and loading protocols on the seismic response of timber shear walls. It was shown that the current test standards include different options for testing and thus cover a wide range of possible uses of timber shear walls in practice. However, it can be noted that some test parameters (e.g. the loading rate) or result evaluation procedures can affect the lateral load-bearing capacity and also the energy dissipation of a timber shear wall system. Therefore, a direct comparison of the available test results is not always possible. Future research and standardization efforts should therefore aim at a valid comparison of results from different test campaigns and between different laboratories.

Acknowledgements

The research was funded by the project InnoCrossLam, which is supported under the umbrella of ERA-NET Cofund ForestValue by MIZŠ, VINNOVA, FORMAS, STEM, BMLFUW, FNR and MINECO-AEI. ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324.

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