World Conference on Timber Engineering Oslo 2023

BUCKLING ANALYSES OF CROSS LAMINATED TIMBER PANELS

Martina Sciomenta[1], Yuri De Santis[2], Chiara Bedon[3], Massimo Fragiacomo[4]

ABSTRACT: This paper investigates the column buckling behaviour of three-layer Cross Laminated Timber (CLT) panels under compression, from both the experimental and numerical point of view. The main aim of present study is hence to define the expected load-bearing capacity for these composite CLT solutions, and to assess the typical fracture mechanism for two different series of specimens of possible technical interest for construction applications. To this aim, a total of 14 column buckling experiments is carried out. First, a set of 7 homogeneous specimens ("HO" series), which are entirely made of beech, are investigated. Their load-bearing capacity is compared with the column buckling performance of 7 hybrid specimens ("HB" series), whose inner layers are made of Corsican pine. Overall, the experimental analysis gives evidence of a rather stable column buckling capacity for CLT panels, with evidence of major failure mode due to out-of-plane bending phenomena, but also rolling shear and delamination. Finally, further assessment of experimental evidence is provided by extended analytical calculations (based on existing formulations, including the Eurocode 5 approach). Comparative results are discussed in terms of structural performance, capacity, weakness of analytical models for CLT solutions.

KEYWORDS: Cross-Laminated Timber (CLT), beech wood (Fagus sylvatica L.), Buckling, Experimental tests, Load-bearing capacity, Standards

1 INTRODUCTION

In the last years the Cross Laminated Timber (CLT) has become a widespread construction material in the framework of panel mid- and high-rise buildings [1]. The high prefabrication and the well-known advantages [2], such as the high dimensional stability, the elevated in-plane isotropic strength and stiffness with respect to sawn timber and the high speed of installation [3] contributed to spread their applicability, in addition with the great environmental benefits, in terms ot carbon absprtion and sustainability.

Several researches have been carried on to assess how and which parameters mainly influence the load-bearing capacity of this engineered wood product.

The results confirmed that the response of CLT is influenced by the lamellas' material and geometry, and in particular by: *i)* the layer thickness [4,5] ; *ii)* the wood species [6,7], and *iii)* the type of adhesive [8,9].

The choice of wood species is so relevant that different studies focused on this point even to emphasize the potential use of wood species other than fir and spruce [10,11,12] which are the most widespread used for commercial applications.

In this framework, native hardwoods species such as beech which is extensively available in European forests [13] proved to have relevant mechanical features for CLT structural applications [14]. Many researches have been also conducted to better understand the CLT behavior under different load conditions as bending [15], compression [16,17], and shear [18,19], nevertheless the CLT in-plane behavior under compressive loads, leading to column buckling is currently poorly investigated as for softwood [20,21] as for hardwood species.

For timber structural components and systems, stability issues have a critical role in design procedures, due to the challenging trend of modern applications towards the construction of high-rise timber buildings as well for the intrinsic material's nature.

In particular, due to the low modulus of elasticity parallel to the grain of timber in general and of the even lower shear modulus which affects the ortogonal layers, CLT is more prone to undergo instability phenomena.

CLT members, depending on the boundary conditions, can be addressed as: *i)* one-way elements if they are restrained on two opposite sides; or as *ii)* two-way elements if them are constrained on three or all sides.

Few studies that have addressed the buckling behavior of CLT members considered them as one-way elements [22]. Some researchers have been carried by performing experimental tests; [23] investigated the axial compression behavior of both cross-laminated timber columns (CLTCs) and control glued-laminated timber columns (GLTCs). It was discovered that CLT column specimens had better ductility and energy absorption. [24] carried on tests on Chilean radiata pine CLT panel, focalizing on the variation of the number of layers while keeping the panel thickness constant. At last, the test

[1] Martina Sciomenta, University of L'Aquila, Italy, martina.sciomenta@univaq.it
[2] Yuri De Santis, University of L'Aquila, Italy, yuri.desantis@.univaq.it
[3] Chiara Bedon, University of Trieste, Italy, chiara.bedon@dia.units.it
[4] Massimo Fragiacomo, University of L'Aquila, Italy, Massimo.fragiacomo@univaq.it

https://doi.org/10.52202/069179-0361

evidences were compared with the numerical predictions and successfully validated.

Kudo *et al*. [25] conducted a series of buckling tests on full-size Japanese Cedar or Japanese Cypress CLT members. The buckling loads were compared with those calculated following the formulas of the Japanese Building Code; it was found that the formulas given in the national standard provided conservative results.

The worldwide standards (i.e. Eurocode 5 [26]) and national codes available for the calculation methods of the buckling capacity (or the stability coefficient) of axially loaded CLT members are only applicable to one-way CLT members.

The currend handbook/standards provide two methods for the calculation of the load-bearing capacity of axially compressed columns with and without eccentricity; the most simple one is based on the Effective Length Method (ELM), while, the other accounts for a 2nd order analysis of the structure. This latter, by the way, considers timber as an elastic material so, is not able to take into account its material non-linearity. The ELM assumes a simple equivalent column hinged at both ends. The simplicity of the approach is that the P-delta effect is taken implicitly into account through a buckling factor, k_c. The buckling factor has the role to reduce the compressive strength of the timber column, in the direction parallel to the grain, and strictly depends on the effective length of the structural element, which is conventionally expressed in terms of slenderness ratio λ.

2 EXPERIMENTAL TESTS

The herein reported buckling tests are part of a wider experimental campaign [27,28] performed at the Laboratory of Structures, Tests and Materials of the University of L'Aquila (Italy), aiming to investigate the possible structural applications of two of the most interesting Italian broad-leaved and conifer timber species, namely beech and Corsican pine [14].

The raw material for both species came from Calabrian forests – South Italy. A list of different preliminary steps was carried out to obtaining the final composition of investigated CLT specimens. Boards were at first strength graded according to EN 14081-2:2018 rules [29] by the grading machine ViSCAN-Portable (Mi-CROTEC). The machine settings used for the strength grading of the boards of both beech and pine were developed in previous studies [30,31,32]. The strength class combinations used to qualify the raw material were D40 and rejects for beech and C20 and rejects for pine (EN 338:2016 [33]). The outcomes are summarized in Table 1. Boards were planed to a thickness of 18 mm to guarantee the adequate planar surface necessary for the face gluing. Two different series of three-layer CLT panels, made respectively of beech and Corsican pine and only beech, were realized by bonding the boards and gluing them with a Melamine Urea Formaldehyde (MUF) adhesive (GripProTM Design – AkzoNobel). The narrow board edges were not bonded. The average of glue grammage was 190 g/m^2. The adhesive was applied in a factory condition of 17° C, with an environmental moisture of 50%. Formed panels were then cold-pressed for two hours, with a pressure of 1.4 N/mm^2.

Table 1: *Mean properties of timber species, as derived from the non-destructive measurements [14].*

Timber species	ρ (kg/m^3)	MOE_{dyn} (N/mm^2)	MoR (N/mm^2)	MOE_{global} (N/mm^2)
Beech	756	16077	80.1	16154
Corsican Pine	512	9650	38.2	9748

Seven specimens for each series were tested under central axial compression loading conditions.

The specimens' geometrical features are characterized by nominal dimensions equal to b=144 mm, t=54 mm and l=800 mm. The three constituent layers had identical nominal thickness t_i = 18 mm.

The buckling tests were carried out by applying a central axial compression on the top surface of the CLT specimens for an average duration of 30 minutes. This condition was pledged by a setup able to provide the desired loading and boundary conditions to the tested CLT beams (Fig. 1).

Each specimen was positioned between a couple of one-way knife hinges whose shape has been designed to ensure the right positioning in the underlying and overlying wedges. The distance between the axes of end hinges was set equal to L=1064 mm.

The horizontal displacements in the loading stage were measured by using four laser displacement transducers, which were placed perpendicularly to the lateral surfaces of each specimen (Fig. 1). In particular, two transducers were located at the midpoint and two near the corners, to account for possible torsional phenomena (Fig.1). Displacement-control tests with a limit of 15 mm to the vertical lowering of the machine crossbeam were carried out by means of an Instron-Schenck machine system. Load vs. mid-span deflections of each beam specimen was monitored and plotted with a sampling rate of 0.5 Hz. Two different speed rates were taken into account during each experiment. At first, until the critical load was reached for each sample, was set equal to 0.44 mm/s. Once the critical load was reached, the speed rate was then reduced to 0.33 mm/s.

https://doi.org/10.52202/069179-0361

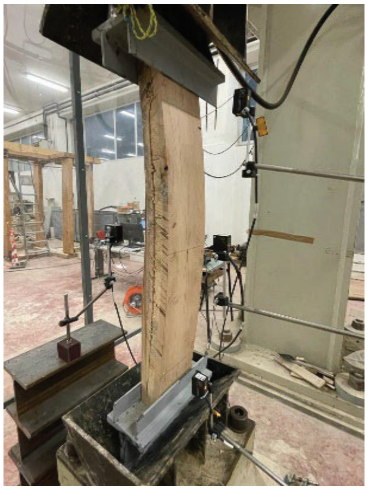

Figure 1: *Experimental tests setup*

The experimental evidences related to buckling test are summarized in Table 2 and Table 3. For most of tested HO and HB samples, the typical failure mode was characterized by out-of-plane bending deflection due to buckling (all the HO specimens except for the HO-6 and HB-1). Nevertheless, rolling shear (HB-2, HB-3 and HB-5) and delamination phenomena (HB-6 and HB-7) occurred in a certain stage of the tests, especially for HB specimens. Typical failure mode outcomes are summarized in Fig. 2.

Figure 2: *Failure modes: left) compressed fibres; right) rolling shear*

Table 2: *Buckling tests experimental evidences for HO= homogeneous series. Failure mode key: b= bending / buckling; r= rolling shear; d= delamination; s_y= the standard deviation, m_k =5th percentile*

ID	F_b (kN)	v_{max} (mm)	Failure Modes
HO -1	211	9.3	b
HO -2	183	4.9	b
HO -3	165	11.6	b
HO -4	203	5.0	b
HO -5	205	4.0	b
HO -6	218	2.4	d
HO -7	217	7.2	b
Average	200	6.3	
s_y	200	6.3	
m_k	19	3.2	

Table 3: *Buckling tests experimental evidences for HB= hybrid series. Failure mode key: b= bending / buckling; r= rolling shear; d= delamination, s_y= the standard deviation, m_k =5th percentile*

ID	F_b (kN)	v_{max} (mm)	Failure Modes
HB -1	234	3.6	b
HB -2	187	6.3	r
HB -3	134	14.0	r
HB -4	241	2.7	r+d
HB -5	204	2.5	r+d
HB -6	204	2.1	d
HB -7	141	11.4	d+b
Average	192	6.1	
s_y	41	4.8	
m_k	99	-4.6	

3 BUCKLING FORMULATIONS

In a typical column buckling analysis, two key aspects should be considered, namely: *i)* a geometric effect called P-delta, which describes the non-linear increasing of deformations due to the increasing eccentricity of the axial load, and *ii)* the non-linear behaviour of timber material under compression actions parallel to the grain. A large investigation on the P-Delta effect on axial compressed timber elements was carried on by Tetmajer *et al* [34] and confirmed by test campaign by Larsen and Pedersen [35], the influence of non-linearity of timber on the interaction between moment and axial force was numerically defined by Buchanan [36].

In this section, a comparison of commonly used analytical formulas for the critical buckling load evaluation was provided. At first, the Euler formulation for column buckling is defined; at a second stage, it is extended in order to account for a possible initial geometric curvature. Thereafter, the existing Eurocode 5 formulation for timber columns subjected to combined bending and axial compression parallel to the grain is discussed.

The buckling strength of CLT specimens under in-plane vertical compression could be provided by classical analytical formulations of axially compressed, monolithic columns [37]. The corresponding Eulerian critical load could be reasonably estimated as:

$$P_e = \frac{\pi^2 E I_{\mathrm{ef}}}{l_0^2} \tag{1}$$

with:

https://doi.org/10.52202/069179-0361

$$I_{\text{ef}} = \frac{bt_i^2}{12} + (bt_i) \cdot \left(\frac{t_i}{2}\right)^2 \tag{2}$$

The flexural moment of inertia, for outer layers and for the inner layer; and

$$l_0 = \beta L \tag{3}$$

with l_0 the effective buckling length.

In Eq.(3), L is the maximum distance between the hinges center, while β is the buckling coefficient accounting for the actual restraint conditions, in this study it was set equal to 1 for pinned-pinned specimens.

The latter Eq. (1) describes the behaviour of an ideal compressed beam (Eulerian instability), without taking into account the material non-linearity as well the possible geometrical clearances caused by production tolerances that lead to an inevitable rectilinear imperfection, which must be taken into account when calculating the buckling load. To take into account this phenomenon, the initial specimen deflection must be considered. A stability analysis of the beam in its deformed configuration was carried out.

The initial deformation is schematized as in Fig. 4, by imposing a sinusoidal deformation where represents its maximum amplitude:

$$\bar{v}(x) = e_0 \, sin\left(\frac{\pi \cdot x}{L}\right) \tag{4}$$

The elastic displacement behaviour can be hence modelled as:

$$Pv(x) = -EI_{\text{ef}}\big(v''(x) - \bar{v}''(x)\big) \tag{5}$$

which can be rewritten as:

$$v''(x) + \alpha^2 v(x) - \bar{v}''(x) = 0 \tag{6}$$

Where

Replacing Eq. (4) and (1) in Eq. (6) and solving, the solution of differential equilibrium equation is:

$$v(x) = e_0 \frac{1}{1 - \frac{PL^2}{\pi^2 EI_{\text{ef}}}} sin\left(\frac{\pi x}{L}\right) = e_0 \frac{1}{1 - \frac{P}{P_e}} sin\left(\frac{\pi x}{L}\right) \tag{7}$$

Its maximum displacement is reached in the middle point of the beam:

$$v\left(\frac{L}{2}\right) = e_0 \frac{1}{1 - \frac{P}{P_e}} \tag{8}$$

The limit load can be written as

$$P = \left(\frac{\alpha L}{\pi}\right)^2 P_e \tag{9}$$

3.1 EUROCODE 5

Based on the Eurocode 5 [26] approach, the buckling verification of timber columns subjected to combined bending and axial compression parallel to the grain is performed by taking into account its minimum relative slenderness ratio:

$$\lambda_{\text{rel}} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0,05}}} \tag{10}$$

with

$$\lambda = \frac{l_0}{\rho_{min}\sqrt{\frac{A}{I_{\min}}}} \tag{11}$$

with A the cross-sectional area, $f_{c,0,k}$ is the characteristic compressive strength parallel to the grain, $E_{0.05}$ represents the fifth percentile value of the MOE parallel to the grain, β=1 is the factor for buckling depending on the support conditions and the load, L is the element length. The stability check of the member in pure compression requires that the design compressive stress $\sigma_{c,0,d}$ along the member would satisfy the condition:

$$\sigma_{\text{c,0,d}} \leq k_c \cdot f_{\text{c,0,d}} \tag{12}$$

where $f_{c,0,d}$ represents the design compressive strength in the direction parallel to the grain and k_c is a buckling reduction factor given by:

$$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{\text{rel}}}} \tag{13}$$

With:

$$k = 0.5(1 + \beta_c(\lambda_{\mathrm{rel}} - 0.3) + \lambda_{\mathrm{rel}}^2) \quad (14)$$

βc an imperfection factor equals to 0.2 or 0.1 for solid timber or glued laminated timber and LVL, respectively, while the coefficient $\beta_0 = 0.3$ in Eq. (14) finally, represents the minimum relative slenderness ratio λ_{rel} beyond which flexural buckling phenomena may occur in the column.

3.2 CANADIAN CLT HANDBOOK

According to the Canadian standard [38], when CLT panels are loaded under in-plane axial loads, only the layers with laminations oriented parallel to the applied axial load should be assumed to carry that load.
The compressive resistance is calculated as:

$$F_{\mathrm{b}} = 0.8 K_C K_{Zc} f_{c,0,d} A_{eff} \quad (15)$$

Where A_{eff} is the effective cross-sectional area of the panel accounting only for the layers with laminations oriented parallel to the axial load, K_C is the slenderness factor for compression members:

$$K_C = \left(1 + \frac{f_{c,0,d} K_{Zc} C_c^3}{35E}\right)^{-1} \quad (16)$$

Where E is the modulus of elasticity of the laminations oriented parallel to the axial load, K_{Zc} is the size factor for compression:

$$K_{Z,c} = \min(6.3\left(2\sqrt{3} r_{eff} l\right)^{-0.13}; 1.3) \quad (17)$$

Where r_{eff} is the radius of gyration accounting only for the layers with laminations oriented parallel to the axial load. C_c is the slenderness ratio:

$$C_c = \min(\frac{l}{\sqrt{12} r_{eff}}; 43) \quad (18)$$

3.3 CLT HANDBOOK U.S. EDITION

According to the U.S Edition of CLT handbook [39], for wall design, the failure load is given by the product of the adjusted compression strength for buckling times the area of the laminations where the grain is running parallel to the load.

$$F_{\mathrm{b}} = C_p f_{c,0,d} A_{eff} \quad (19)$$

Where the column stability reduction factor is:

$$C_p = \frac{1 + \mathrm{P_{cE}}/\mathrm{P_c^*}}{1.8} - \sqrt{\left(\frac{1 + \mathrm{P_{cE}}/\mathrm{P_c^*}}{1.8}\right)^2 - \frac{\mathrm{P_{cE}}/\mathrm{P_c^*}}{1.8}} \quad (20)$$

Where $\mathrm{P_c^*}$ is the composite compression capacity and:

$$\mathrm{P_{cE}} = \frac{\pi^2 EI_{app-min}}{l^2} \quad (21)$$

The minimum value of the apparent stiffness is to be determined as:

$$EI_{app-min} = 0.5184 EI_{app} \quad (22)$$

EI_{app} is a reduced effective bending stiffness to account for shear deformation.

4 COMPARISON WITH EXPERIMENTAL RESULTS

Table 2 summarize the average experimental loads and the predicted loads by means of standards formulations. The closest prediction is given by the Eurocode 5 formulation. It is worth noting that Canadian standard predict the same failure load for both homogenous and hybrid configurations. The Canadian standard completely neglect the mechanical properties of the layers perpendicular to the load. In the American standard the influence of the mid-layer is accounted only in the apparent stiffness calculation, while the effective area refers only to layers parallel to the load. The American standard predictions for the two cases are close together.

Table 2: *Comparison between experimental failure loads and predicted loads via standards formulations (HO= homogeneous; HB= hybrid).*

		F_b (kN)	F_b/N_c	Scatter (%)
HO	Experimental	200		
	Eurocode 5	210	0.92	4.9
	Canad.Handb	176	0.88	-12.3
	U.S. Handb.	156	0.78	-21.9
HB	Experimental	192		
	Eurocode 5	194	0.93	1.0
	Canad.Handb	176	0.88	-8.5
	U.S. Handb.	157	0.78	-18.5

5 CONCLUSIONS

Among others, stability issues are particularly critical in timber load-bearing components, due to their intrinsic anisotropy and to the increasing trend towards challenging high-rise timber buildings. As such, this possible vulnerability is even more pronounced for Cross Laminated Timber (CLT) components, due to their intrinsic composition and layout.
In this paper, a major attention was given to the column buckling behaviour of three-layer CLT panels. Technical advantage for the assessment of load-bearing capacity, failure mode and potentials was based on a set of experimental tests and also analytical models. Two different configurations were considered, the first (HO) composed of three layers made with the same timber specie, whereas the second was assembled with the inner layer made of a different timber specie (HB). Overall, the tested panels (14 in total) showed different failure mechanisms but little scattered results in terms of load-bearing capacity. Specifically, the hybrid (HB) specimens resulted in standard deviation.
In terms of analytical estimation of actual CLT capacities in column buckling setup, the attention was given to existing analytical models of literature, including the existing Eurocode and Handbook formulations.

https://doi.org/10.52202/069179-0361

Most importantly, the results provided by the analytical formulation, even though very close to the experimental ones, resulted always in favour of safety, since the analytical limit loads were found smaller than those obtained experimentally.

REFERENCES

[1] Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. European *Journal of Wood and Wood Products*, 74(3). https://doi.org/10.1007/s00107-015-0999-5

[2] Jeleč, M., Varevac, D., Rajčić, V.: Cross-laminated timber (CLT) – a state of the art report, *GRAĐEVINAR*, 70 (2018) 2, pp. 75-95, doi: https://doi.org/10.14256/JCE.2071.2017

[3] Van De Kuilen J.W.G., Ceccotti A., Xia Z., He M.,Very Tall Wooden Buildings with Cross Laminated Timber, *Procedia Engineering*, Volume 14, 2011, Pages 1621-1628, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2011.07.204

[4] Sikora K. S., McPolin D. O., and Harte A. M., "Effects of thickness of cross-laminated timber (CLT) panels made from Sitka spruce on mechanical performance in bending and shear," *Constr. Build. Mater.*, vol. 116, pp. 141–150, 2016.

[5] Wang, Z.; Fu, H.; Gong, M.; Luo, J.; Dong, W.; Wang, T.; Chui, Y.H. Planar shear and bending properties of hybrid CLT fabricatedwith lumber and LVL.*Constr. Build. Mater*. ,151, 172–177. 2017

[6] Yusoh, P. M. Tahir, M. K. A. Uyup, S. H. Lee, H. Husain, &M. Khaidzir. "Effect of wood species, clamping pressure and glue spread rate on the bonding properties of cross-laminated timber (CLT) manufactured from tropical hardwoods." *Construction and Building Materials*. 2020. doi: 121721. 10.1016/j.conbuildmat.2020.121721.

[7] Azambuja R.R, DeVallance D., McNeel. J. "Evaluation of Low-Grade Yellow-Poplar (Liriodendron tulipifera) as Raw Material for Cross-Laminated Timber Panel Production." *Forest Products Journal*. 72. 2022. Doi: 1-10. 10.13073/FPJ-D-21-00050.

[8] Adnan N. A., Tahir P. Md., Husain H., Lee S.H. , Khairun Anwar Uyup M., Arip M. N. M. & Ashaari Z.. "Effect of ACQ treatment on surface quality and bonding performance of four Malaysian hardwoods and cross laminated timber (CLT)". European *Journal of Wood and Wood Products*. 2021.

[9] Musah M., Wang X., Dickinson Y., Robert R., Rudnicki M. & Xie X.. "Durability of the adhesive bond in cross-laminated northern hardwoods and softwoods." *Construction and Building Materials*. 2021. doi: 307. 124267. 10.1016/j.conbuildmat.2021.124267.

[10] Aicher S., Christian Z., and Dill-Langer G., "Hardwood glulams – emerging timber products of superior mechanical properties," Sep. 2014, doi: 10.13140/2.1.5170.1120.

[11] Franke S., "Mechanical properties of beech CLT," in *WCTE 2016* - World Conference on Timber Engineering, 2016.

[12] Crovella P., & Kurzinski S.. "Predicting the Strength and Serviceability Performance of Cross-laminated Timber (CLT) Panels Fabricated with High-Density Hardwood." in *WCTE 2020* - World Conference on Timber Engineering, 2021.

[13] Kovryga, S. Peter, and Jan Willem G van de Kuilen, "Mechanical properties and their interrelationships for medium-density European hardwoods, focusing on ash and beech," *Wood Mater. Sci. Eng*., pp. 289–302, 2019, doi: https://doi.org/10.1080/17480272.2019.1596158.

[14] Sciomenta M., Spera L., Bedon C., Rinaldi V., Nocetti M., Brunetti M., Fragiacomo M., Romagnoli M. "Mechanical characterization of novel Homogeneous Beech and hybrid Beech-Corsican Pine thin Cross-Laminated timber panels". *Constr. Build. Mater*., vol. 271, 2021, doi: 10.1016/j.conbuildmat.2020.121589

[15] Pang, S.-J.; Jeong, G.Y. Effects of combinations of lamina grade and thickness, and span-to-depth ratios on bending properties ofcross-laminated timber (CLT) floor. *Constr. Build. Mater*.,222, 142–151. 2019

[16] Gong, Y.; Ye, Q.; Wu, G.; Ren, H.; Guan, C. Effect of size on compressive strength parallel to the grain of cross-laminated timbermade with domestic larch.Chin. *J. Wood Sci. Technol*. ,35, 42–46. 2020a.

[17] Gong, Y.; Ye, Q.; Wu, G.; Ren, H.; Guan, C. Prediction of the compressive strength of cross-laminated timber (CLT) made bydomestic Larix Kaempferi. *J. Northwest For. Univ*.,35, 234–237. 2020b

[18] Li, Q.; Wang, Z.; Liang, Z.; Li, L.; Gong, M.; Zhou, J. Shear properties of hybrid CLT fabricated with lumber and OSB. *Constr.Build. Mater*.,261, 120504. 2020

[19] Wang, F.; Wang, X.; Yang, S.; Jiang, G.; Que, Z.; Zhou, H. Effect of different laminate thickness on mechanical properties of cross-laminated timber made from Chinese fir. *Sci. Silvae Sin*.,56, 168–175.13. 2020

[20] Perret O., Douthe C., Lebée A., Sab K., 'A shear strength criterion for the buckling analysis of CLT walls', *Engineering Strucutres*, Vol. 211, 2020. https://doi.org/10.1016/j.engstruct.2020.110344

[21] Ye Q, Gong Y, Ren H, Guan C, Wu G, Chen X. Analysis and Calculation of Stability Coefficients of Cross-Laminated Timber Axial Compression Member. *Polymers* (Basel). 2021 Dec 6;13(23):4267. doi: 10.3390/polym13234267.

[22] Ye Q, Gong Y, Ren H, Guan C, Wu G, Chen X. Analysis and Calculation of Stability Coefficients of Cross-Laminated Timber Axial Compression Member. *Polymers* (Basel). 2021 Dec 6;13(23):4267. doi: 10.3390/polym13234267.

[23] Wei, Peixing & Wang, Brad & Li, Hao & Wang, Libin & Peng, Si & Zhang, Long. (2019). A comparative study of compression behaviors of cross-laminated timber and glued-laminated timber columns. *Construction and Building Materials*. 222. 86-95. 10.1016/j.conbuildmat.2019.06.139.

[24] Pina J.C, Saavedra Flores E. I. a, Saavedra K.,b Numerical study on the elastic buckling of cross-laminated timber walls subject to compression, *Construction and Building Materials,* Volume 199, 2019, Pages 82-91, ISSN 0950-0618
[25] Kudo, Y.; Nakajima, S.; Miyatake, A.; Araki, Y.; Shibusawa, T.; Haramiishi, T. Evaluation of buckling strength of cross laminated timber. In Proceedings of the World Conference on Timber Engineering (*WCTE2016*), Vienna, Austria, 22–25 August 2016
[26] EN 1995 Eurocode 5 2003. Design of timber structures, part 1-1: General-Common rules and rules for buildings. CEN/TC 250, European Committee for Standardisation, Brussels.
[27] Sciomenta M., Spera L., Peditto A., Ciuffetelli E., Savini F., Bedon C., Romagnoli M., Nocetti M., Brunetti M., Fragiacomo M., Mechanical characterization of homogeneous and hybrid beech-Corsican pine glue-laminated timber beams, *Engineering Structures*, Volume 264, 2022, 114450, ISSN 0141-0296
[28] Scarascia Mugnozza G, Romagnoli M, Fragiacomo M, Piazza M, Lasserre B, Brunetti M, Zanuttini R, Fioravanti M, Marchetti M, Todaro L, Togni M, Ferrante T, Maesano M, Nocetti M, De Dato GB, Sciomenta M, Villani T (2021). La filiera corta del legno: un'opportunità per la bio-economia forestale in Italia. *Forest@* 18: 64-71. – doi: 10.3832/efor0052-018 [online 2021-08-26]
[29] CEN (European Committee for Standardization), ''Timber Structures – Strength graded structural timber with rectangular cross section – Part 2: Machine grading; additional requirements for type testing," EN 14081-2, 2018.
[30] Nocetti M., Bacher M., Brunetti M., Crivellaro A., van de Kuilen J. W. G., "Machine grading of Italian structural timber: preliminary results on different wood species", in *WCTE 2010* - World conference on timber engineering, 2010
[31] Brunetti M., Nocetti M., Pizzo B., Negro F., Aminti G., Burato P., Cremonini C., Zanuttini R., Comparison of different bonding parameters in the production of beech and combined beech-spruce CLT by standard and optimized tests methods, *Construction and Building Materials*, Volume 265, 2020a, 120168, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2020.120168.
[32] Brunetti, M., Nocetti, M., Pizzo, B. et al. Structural products made of beech wood: quality assessment of the raw material. *Eur. J. Wood Prod*. 78, 961–970, 2020b. https://doi.org/10.1007/s00107-020-01542-9
[33] CEN (European Committee for Standardization), "Structural timber - Strength classes," EN 338, 2016.
[34] Tetmajer L. (1896). Die Gesetze der Knickungs- und der zusammengesetzten Druckfestigkeit der technisch wichtigsten Baustoffe. *Materialprüfungs-Anstalt am Schweiz*. Polytechnikum Zurich. Zurich.
[35] Larsen HJ., Pedersen SS. (1975). Tests with centrally loaded timber columns. In: Proceedings of *CIB-W18 meeting 4*: Paper No. 4-2-1. Paris.
[36] Buchanan AH. (1984). Strength model and design methods for bending and axial load interaction in timber members.
[37] Timoshenko S.P., Gere J.M.(1961). Theory of Elastic Stability, McGraw-Hill, International Book Company
[38] Karacabeyli E., Gagnon S. FPInnovations, Canadian CLT Handbook, 2019 Edition. Volume I
[39] Karacabeyli E., Gagnon S. FPInnovations, U.S Edition CLT Handbook, v2013

https://doi.org/10.52202/069179-0361