STRUCTURE OF OFFICE AND RESIDENTIAL BUILDING IN ROOSEVELT STREET IN BELGRADE

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UDK: 624.011.1.042.7:691.116
DOI: 10.14415/konferencijaGFS2021.08

Summary: *The beginning of the new millennium brought a revolution in the application of timber as a material for the construction of multi-storey buildings for various purposes. The CLT is a European innovative timberbased material in which timber boards, made of home-grown timber species (mainly Spruce) are assembled in layers and glued together crosswise in order to form massive timber wall and floor panels. The crosslamination method gives a material with high stability, good mechanical properties, good thermal insulation and a good behaviour in case of earthquake or fire Cross laminated timber (CLT) is an innovative timber-based product that enables the structural design of multi-storey and high-rise buildings with a number of advantages, of which its seismic behavior stands out. This paper presents the basics of seismic analysis of multi-storey buildings made of cross-laminated timber construction, the way of forming connections of structural elements in accordance with the appropriate seismic load and an overview of specific parameters that are part of the calculation, based on certain experimental observations and state of the art of codes and research in this field.*

Keywords: *cross laminated timber (CLT), structural details, seismic design*

1. INTRODUCTION

Cross laminated timber (CLT) is a sophisticated modern product that has greatly improved the load-bearing capacity of traditional wood as building material. The CLT system (in which CLT stands for cross-laminated solid timber boards) was developed in Switzerland, Austria and Germany around 20 years ago and it's rapidly spreading in most European countries such as Italy and Nordic Countries [1]. In the early 2000s construction with CLT increased dramatically, partially driven by the green building movement, but also due to better efficiencies, code changes, and improved marketing.

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The CLT is a European innovative timberbased material in which timber boards, made of home-grown timber species (mainly Spruce) are assembled in layers and glued together crosswise in order to form massive timber wall and floor panels (Figure 1). The crosslamination method gives a material with high stability, good mechanical properties, good thermal insulation and a good behaviour in case of earthquake or fire.

Figure 1. Cross laminated timber assembly, 5-layered CLT panel and a tall building made of CLT bearing walls

The other characteristic, important for the serviceability of these structures, is its dynamic behaviour and it has been extensively studied in the literature (Damme et al. 2017, Casagrande et al. 2018, Kozaric et al. 2019, Huang et al. 2020). The CLT system can be used for single unit housing and multi-storey buildings. The construction process is very quick and possible even for non-highly-skilled manpower. The CLT panels are strong and stiff whatever is the timber quality, therefore they allow the use of medium-low grades of home-grown sawn timber. An important factor has been the perception that CLT is a 'not light' construction system. European producers have followed a proprietary approach to manufacturing with European Technical Approval (ETA) reports that allow them to operate, however there are efforts under way to develop a European (EN) standard. Typical building types include multi-family apartment, buildings and educational buildings. The countries leading in the use of CLT are: Austria, Germany, Switzerland, Italy, Sweden and Norway. New plants are soon to be built in Sweden, Australia and North America. CLT is also known as X-lam („cross lam'') and „massive timber''. In the last decade many business residential and school buildings was carried out across Europe by using this technology, such as already mentioned. Classic structures of student houses in masonry or skeletal system of construction can be successfully replaced by CLT technology from the reasons given below. CLT now has a global reach, with many large buildings using this material (Cvetkovic et al. 2015, Popovski and Gavric 2016).

2. STATE OF THE ART OF SEISMIC BEHAVIOUR RESEARCH OF CLT HIGH-RISE BUILDINGS

More than half of the world's population lived in cities in 2014 and it is expected that over 70% of it will be living in cities by 2050 [3]. In that sense, high-rise timber building construction has the potential to solve the urgent needs for urban buildings of

the 21st century while minimizing the associated environmental effects. Today's high-rise buildings are built employing structural steel or reinforced concrete which are materials associated with high-energy consumption and significant greenhouse gas emissions throughout their manufacturing, transportation and building processes. Together, structural steel and concrete are the source of approximately 10% of total greenhouse gas emissions from the building industry [4]. In turn, buildings and transportation systems create two-thirds of the total global carbon emissions. By contrast, one cubic meter of wood can store one tonne of CO_2 [3].
Mid-rise construction of 4 to 6-storey timber buildings is possible by means of light-framed construction [6], however, taller buildings of 8 and more storeys require an alternative structure. To this end, massive panels of Cross-Laminated Timber (CLT) can be employed as lateral resisting elements in taller structures. The dynamic response of multi-storey CLT buildings including their seismic design has not yet been fully established [7, 8]. This lack of knowledge is reflected to their seismic design and has limited the potential of tall CLT construction in seismic areas. In fact, current multi-storey CLT buildings are mainly located in low to moderate seismic activity in Europe and Australia as summarized in Table 1.

Table 1. Completed multi-storey and high-rise CLT biuldings

Project	Location	Storey	Height	Units	Complet.
Stadhaus	London, UK	9	30	29	2009
Lomnologen Project	Vaxjo, Sweeden	8	26	134	2009
Bridport House	London, UK	8	25	41	2011
Holz8	Bad Aibling, D	8	25	15	2011
Forte	Melbourne	10	32.2	23	2012
Cenni di Cambiamento	Milan, Italy	9	27	124	2013
Mj∅ starnet	Norway	18	85.4	-	2019
Ho-Ho	Wien, Austria	24	84	-	2019

This table shows multi-storey timber buildings in CLT completed to date. Nonetheless, well-designed and well-constructed timber structures can have a good earthquake response under earthquakes as demonstrated by recent shake table tests and numerical studies. Yet, considerable uplift forces can be experienced on ground floor hold-down connectors due to uplift and overturning seismic moments. Additionally, experimental tests have shown that when multi-storey CLT buildings are subjected to strong ground motions, they might be prone to high floor accelerations at top floor levels [8].
One of the first experimental projects on the lateral response of CLT was carried out by Dujic et al. [10]. CLT panels with different connection details and vertical load levels were tested under monotonic and cyclic loading. The authors concluded that the load-bearing capacity of CLT wall panels is limited by the stiffness of connections and local wood failures are possible. In addition, increasing vertical load levels have advantageous impact on the lateral resistance of CLT wall panels, especially when the connections do not have significant strength. Similarly, Popovski et al. [2] conducted numerous tests on CLT wall panel combinations with different aspect ratios and openings were examined as well as various metal connectors and connector configurations. The authors concluded that angle bracket and hold-down connectors can provide a good level of global ductility

to the system, and therefore could be used in CLT building construction. On the other hand, the SOFIE project is one of the most comprehensive research efforts on the seismic behaviour of CLT systems carried to date which included CLT shear wall panel testing as well as full-scale shake-table experimentation on 3 and 7-storey CLT buildings [8, 10].

Figure 2. „Mjøstårnet" and „Ho-Ho" timber high-rise buildings

Experimental results of this project on different connections and 20 different panel configurations have been summarized by Gavric et al. [12]. Besides, in-plane connections with screws and connections between perpendicular CLT wall panels were also examined. Based on the test results, an average value of over strength factor of 1.74 was recommended. A full-scale 7-storey CLT building was also tested on a shake table [8]. The 7-storey CLT building was designed following EC8 design provisions with a response modification factor (q) of 3. During the shake table tests, the building was subjected to 10 ground-motion records with increasing intensities. Damage was observed at the hold-down connectors due to high overturning demands causing considerable uplift on tension connectors at lower levels. Nevertheless, no residual plastic deformation was experienced and the 7-storey CLT building remained stable throughout. The buildings performed remarkably well even when subjected to severe earthquake motion like that of the devastating Kobe earthquake (M 7,2 and a=0,8-1,2 g). In the case of the 7-storey building there was no residual deformation at the end of the test. The maximum inter-storey drift was 40 mm (1,3%),while the maximum lateral deformation at the top of the building was only 287 mm. High floor accelerations of around 3.8 g were measured at the upper levels of the 7-storey CLT building (Figure 3). The CLT

buildings showed ductile behavior and good energy dissipation. Such behavior was mainly influenced by the mechanical connections used.
Málaga-Chuquitaype et al. [13] carried out a series of cyclic test on CLT panel of different connector configuration and found that the level of vertical loads significantly influences the local ductility of the connectors potentially leading to undesired brittle failure modes.

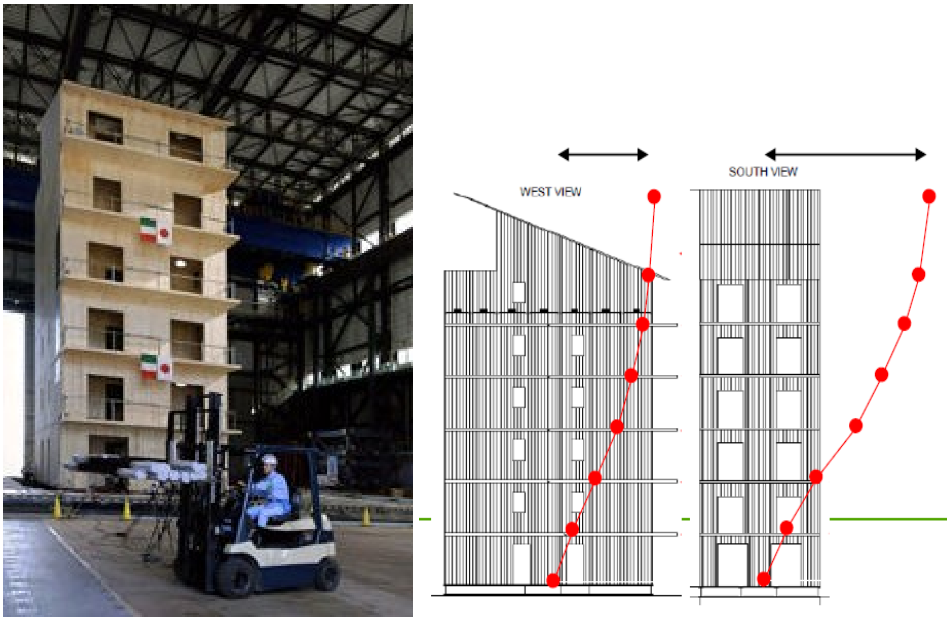

Figure 3. Seismic performance testing in Japan

3. SEISMIC DESIGN CODE OF CLT BUILDINGS IN EUROPE

Despite the fact CLT was invented in Europe around 20 year ago, currently, with the only exception of the product standard (EN 16351 2015), there are no specific design provisions for CLT buildings within the European standards, including EC8 (CEN 2004). Previous practice made reference to the specifications included in the European Technical Approvals (ETA) of the single producers for the calculation of CLT panels and assuming in the seismic design a q-behavior factor equal to 2.0, prescribed for buildings erected with glued walls and diaphragms by EC8. However, the revision of the chapter for the seismic design of timber buildings within EC8 is in progress and will include CLT, as is the revision of the EC5 where CLT will be included as a timber-based product. According to the new specifications in EC8, CLT buildings will be classified as dissipative structures with two different values of the behavior factor q for the ductility class medium (DCM) and ductility class high (DCH). General rules and capacity design rules will be provided both at the building level and at the connection level to avoid any possible global instability or soft-story mechanism at a global level and to prevent any possible brittle failure in the ductile structural elements at a local level. The general rules will include a general description of the structural system, of the main structural components (walls, floors, and roof), type of connections generally used for the CLT system, and some regularity provisions, also common to other structural systems. No limitations on the maximum number of storys will be given. According to these rules, a distinction is made between CLT buildings made of single, monolithic wall elements and CLT buildings made of "segmented walls," (walls composed of more than one panel). Capacity design rules are specified for the two ductility classes DCM and DCH, both at the building level and at the connection level. Regarding the former ones, in DCM, the structural elements which should be designed with overstrength to ensure the development of cyclic yielding in the dissipative zones are:

1) all CLT wall and floor panels,
2) connections between adjacent floor panels,
3) connections between floors and underneath walls, and connections between perpendicular walls, particularly at the building corners.

According to the same requirements, the connections with dissipative behavior are:

1) the shear connections between walls and the floor underneath, and between walls and the foundation and,
2) anchoring connections against uplifts placed at wall ends and at wall openings. In DCH, the rules are the same as for DCM with the sole exception that also,
3) the vertical screwed or nailed step joints between adjacent parallel wall panels within the segmented shear walls shall be regarded as dissipative connections.

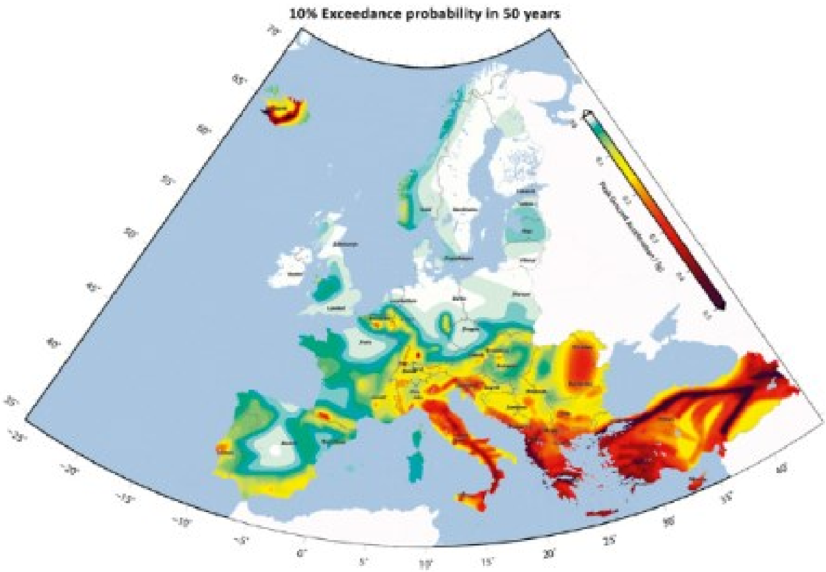

Figure 4. Seismic hazard map for Europe (Giardini et al 2013).

Three alternatives are possible for the ductility classification of the dissipative zones:

1) providing minimum values of the required ductility ratio in quasi-static fully reversed cyclic tests, assuming failure has occurred when a 20% reduction of the resistance from the first to the third cycle backbone curve (CEN 2001) has taken place (values of 3.0 and 4.0 for the ductility ratio of shear walls, holddowns, angle brackets, and screws, respectively, for DCM and DCH),
2) following prescriptive provisions on the diameter of fasteners and connected member thicknesses, or
3) ensuring the attainment of a ductile failure mode characterized by one or two plastic hinge formation in the metal fastener according to the European Yield Model (EYM).

4. BEHAVIOUR FACTOR OF CLT STRUCTURES

The q-behaviour factor is used to perform the seismic design of a building by means of linear analyses with the response spectrum. To this aim, the q-factor is necessary to scale down the elastic response spectrum to the design spectrum; it accounts for the non-linear behaviour of the structure, the presence of damping and of any other forcereducing effect. The current version of Eurocode 8 [14] does not prescribe any specific q-factor for CLT structures; a q-factor equal to 2.0 is prescribed for buildings erected with glued walls and diaphragms that comply with the criterion of regularity in elevation. However, this building typology cannot be intended as a CLT structural system, because the investigations on the seismic performance of panelised buildings have been conducted after the publication of the standard.
Among the experimental approaches, the most used method to assess the q-behaviour factor of a CLT structure uses the results of fullscale shaking table tests. In particular, the q-factor is defined as the ratio of the Peak Ground Acceleration (PGA) at which the near-collapse status is reached to the PGA with which the building was designed elastically [15]. Conversely, when numerical approaches are used, the q-factor is assessed using the results of non-linear simulations carried out under static or dynamic loading conditions [8,16,17]. The models are developed using the static ductility and hysteresis cycles resulting from tests of single components (wall systems and mechanical connections). In table 2 is shown that the highest q-factors are obtained when segmented walls composed of narrow panels and vertical step joints are considered and the lower values are obtained when monolithic walls are adopted. Differences are due to the enhanced energy dissipation in the vertical step joints, which occurs when fasteners with a small diameter are used. Furthermore, Trutalli and Pozza [18] showed that the regularity in elevation influences the q-factor, reducing its value up to 25%.

Table 2. Values of the q-behaviour factor recommended in the literature

Reference	Method	Value
Ceccotti and Follesa	Shaking table test of a 3-storey structure with narrow walls	3.4
Ceccotti et al.	Shaking table test of a 7-storey structure with narrow walls	3.0
Flatscher and Schickhofer	Shaking table test of a 3-storey structure with large walls	2.8
Pei at al.	Similations of full-scale structures with narrow walls	4.5
Pozza and Trutalli	Similations of full-scale structures with large walls	2.0
Popovski and Karacabeyli	Single components tests (connection and CLT wall systems)	3.0
Popovsky at al.	Similations of full-scale structures with narrow walls	3.0

5. CONCLUSION

The seismic behaviour of CLT structures dominantly depends on the performance of the connections, while the timber panels act almost as rigid bodies. This means that, under dynamic conditions, the dissipative connections shall withstand large deformations and provide a stable energy dissipation. Despite the fact CLT was invented in Europe around 20 year ago, currently, with the only exception of the product standard (EN 16351 2015), there are no specific design provisions for CLT buildings within the European standards, including EC8 (CEN 2004).

The assessment of the q-behaviour factor of a CLT structure has been a central topic of many research projects. The investigations have been carried out using both experimental and numerical approaches, and different analysis methods have been proposed. In this context, due to the high costs of testing, numerical methods have played a key role in the assessment of the q-factor for CLT structures. Their advantage relies on the possibility of investigating the q-behaviour factor by varying the geometry of the buildings (number of storeys, plan dimensions, aspect ratio of the CLT members, and properties of the connections), the applied loads, and the ground motion record.

REFERENCES

[1] Cvetkovic, R., Stojic, D., Krasic, S., Markovic, N.: Innovative structural CLT system in projecting and building of student houses. *Facta universitatis-series: Architecture and Civil Engineering,* **2015**.*,* vol. 13(1): p.p. 57-64.

[2] Popovski, M., Gavric, I.: Performance of a 2-Story CLT house subjected to lateral loads. *Journal of Structural Engineering,* **2016** 142(4): p.p. 1-12.

[3] Sarkisian, M.: *Designing Tall Buildings – Structure as Architecture.* Routledge, Taylor and Francis Group. New York and London, **2012**.

[4] Green, M.:Wood Works. Retrieved from www.woodworks.org/download **2012**.

[5] Damme, B.V., Schoenwald, S., Zemp, A.: Modeling the bending vibration of cross-laminated timber beams. European Journal of Wood and Wood Products, **2017**., 75: p.p. 985–994.

[6] Pei, S, Van de Lindt, J, Popovski, M, Berman, J, Sause, R, Blomgren, H, and Rammer, D.: Progress on the development of seismic resilient tall CLT buildings in the Pacific Northwest. *World Conference on Timber Engineering.* **2014**. Quebec City, Canada.

[7] Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., and Kawai, N.: SOFIE project-3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering Structural Dynamics*. **2013** 42(13), p.p. 2003-2021.

[8] Ceccotti, A.: New technologies for construction of medium-rise buildings in seismic regions: The XLAM case. Structural Engineering International, **2008**. 18(2). p.p.156-165.

[9] Danielsson, H., Serrano, E.: Cross laminated timber at in-plane beam loading. Prediction of shear stresses in crossing areas. *Engineering Structures,* **2018.** 171, p.p. 921-927.

[10] Dujic, B, Puceli, J, and Zarnic, R.: Testing of racking behaviour of massive wooden wall panels. Proceedings of 37th CIB-W18 Meeting. International Council for Building Research and Innovation, 2004. Rotterdam, Netherlands.
[11] Espinoza, O., Rodriguez-Trujillo, V., Laguarda-Mallo, M.F., Buehlmann, U.: Cross-laminated timber: status and research needs in Europe. *BioResources,* **2016**. 11(1): p.p. 281-295.
[12] Gavric, I., Rinaldin, G., Amadio, C., Fragiacomo, M., Ceccotti, A.: Experimental-numerical analysis of the seismic behavior of cross-laminated wall systems. *World Conference of Earthquake Engineering*, **2012**, Lisbon, Portugal.
[13] Málaga-Chuquitaype C, Skinner, J, Dowdall, A, Kernohan, J.: Response of CLT shear walls under cyclic loads, *World Conference on Timber Engineering*, **2016**. Vienna, Austria.
[14] EN 1998–1:2004/A1. Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings. CEN, Brussels, Belgium; **2013**.
[15] Ceccotti A, Sandhaas C.: A Proposal for a standard procedure to establish the seismic behaviour factor q of timber buildings. *World Conference on Timber Engineering*, **2010.** Riva del Garda, Italy.
[16] Pozza L., Trutalli D.: An analytical formulation of q-factor for mid-rise CLT buildings based on parametric numerical analyses. *Bull. Earthq. Eng*. **2017.** 15(5): p.p. 2015–2033.
[17] Pozza L., Scotta R., Trutalli D., Polastri A.: Behaviour factor for innovative massive timber shear walls. *Bull. Earthq. Eng*. **2015**;13(11): p.p. 3449–3469.
[18] Trutalli D., Pozza L.: Seismic design of floor-wall joints of multi-storey CLT buildings to comply with regularity in elevation. *Bull. Earthq Eng***. 2018**;16(1): p.p. 183–201.

SEIZMIČKI PRORAČUN I KONSTRUKCIJSKO OBLIKOVANJE VIŠESPRATNIH OBJEKATA GRAĐENIH U UNAKRSNO LAMELIRANOM DRVETU

Rezime: *Početak novog milenijuma doneo je revoluciju u primeni drveta kao materijala za gradnju konstrukcija višespratnih objekata različite namene. Unakrsno lamelirano drvo (CLT-cross laminated timber) je inovativni proizvod na bazi drveta koji omogućava konstrukcijsko oblikovanje višespratnih objekata uz niz prednosti od kojih se izdvaja njegovo aseizmičko ponašanje. U ovom radu date su osnove seizmičke analize višespratnih objekata izvedenih u konstrukciji od unakrsno lameliranog drveta, način oblikovanja veza konstrukcijskih elemenata u skladu sa odgovarajućim seizmičkim opterećenjem i pregled specifičnih parametara koji su deo proračuna, a zasnovani su na određenim eksperimentalnim opservacijama.*

Ključne reči: *unakrsno lamelirano drvo, konstrukcijski detalji, seizmička analiza.*