MARSHALL PLAN SCHOLARSHIP REPORT

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Research title: Design of mid-size Cross Laminated Timber (CLT) building according to European building codes

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Disclaimer

This report is prepared according to personal experiences during three month summer visit funded from Marshall Plan scholarship. There is no warranty for validity of data and the writer does not assume any responsibility for the accuracy or completeness of this document

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Design of mid-size Cross Laminated Timber (CLT) building according to European building codes

Abstract

Cross laminated timber (CLT) is a new engineered wood material with a wide range of application as structural member in residential, commercial and educational buildings. CLT is developed in Austria and its production and application is increasing in Europe and around the world. One of the utilization fields of CLT is midrise residential and commercial buildings including single and multi-family residential buildings, educational institutions, and office buildings. The presented report is prepared based on a three month research project for being introduced to Austrian CLT producers and CLT related companies, implementations of CLT panels in buildings and European standard for designing of CLT buildings. An example midrise building design was considered for the project. The two and three dimensional drawing was prepared in Revit software. Focusing on designing of different wall and floor components, the final size of designed wall and floor elements obtained according to calculated design values utilized with CLT Engineering software.

Introduction

Cross Laminated Timber (CLT) was developed in Austria approximately two decades ago (Lehmann 2012) and has been well-established in European countries especially Austria. CLT is made of different layers of lumber crossing each other with the angle of 90 degree, in which each layer individually consisted of different lumber in the same direction (Brandner, Flatscher et al. 2016). The number of layers is uneven usually and number of layers depends on the final application of panels (Fig. 1).

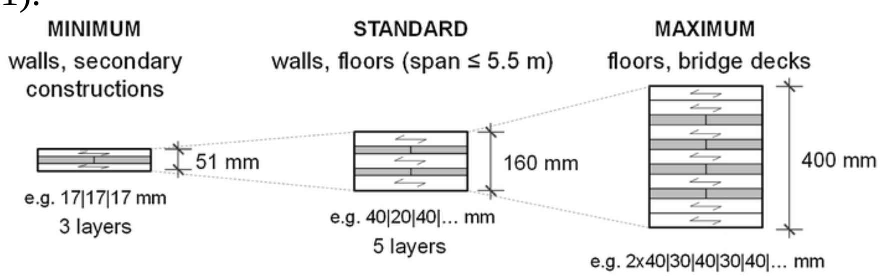


Fig. 1 Examples of different layups of CLT layers for different applications (Schickhofer, Brandner et al. 2016)

This new engineering wood product has been used for a wide range of construction applications, including single and multi-family residential buildings, educational institutions, and office buildings (Mallo and Espinoza 2015). While this product has been experienced twenty years of use in the European countries, it is still at the early stages of use and commercialization as a construction material in the United States. Architects and designers are aware of CLT and currently research work on CLT panels is increasing; therefore a promising future for CLT construction within the United States is being expected. As indicated in (Mallo and Espinoza 2014) between being aware and proficient there is a lack of education, knowledge and experiences in the use and construction of CLT buildings. On the other hand, because of the existence of a good background of working on CLT as a structural material and the way that it is being utilized in buildings and structures in Austria, abundant information has been generated. Therefore the presented research aim was to take advantage of the great knowledge of previous experiences. The main research goal was designing of a mid-size CLT building according to European building codes and the minor objective were being introduced to Austrian CLT producers companies, implementations of CLT panels in buildings and to European standard for designing of CLT buildings.

Sustainable midrise buildings

Buildings are responsible for more than 40 percent of global energy use and one third of global greenhouse gas emissions, both in developed and developing countries (UNEP 2009). With the growing population, it has been predicted that by 2060 the world population will increase by 30% (Roser and Ortiz-Ospina 2017). The population growth leads to the increasing demands for more buildings and therefore more building material. Because of the negative environmental effects of buildings constructed using common building materials such as concrete and steel, sustainable buildings are becoming more and more popular and their growth is expected to be continued in the future. The advancement in understanding of timber building behavior, along with the refinement of engineered wood products design and performance has demonstrated the applicability of using wood as a primary structural support system in mid-rise building construction (Robertson, Lam et al. 2012). Mid-rise CLT buildings (including residential and nonresidential) could be considered as alternatives to the current steel and concrete buildings and fulfills the requirements of green building material. With the successful earthquake test conducted on 3 and 7 story building in Japan, the efficient use of CLT as a multistory building material has been approved (Ceccotti 2008).

In Europe CLT competes with other building material for construction of midrise buildings (Espinoza, Rodriguez Trujillo et al. 2015) and its production is increasing. Global production of CLT was about 625 thousand m^3 in 2014, and it was being furcated to be increased to about 700 thousand m^3 in 2015 (Fig. 2). About 90% of worldwide CLT production is located in Europe and 60% of it is belonged to Austria (Espinoza, Rodriguez Trujillo et al. 2015).

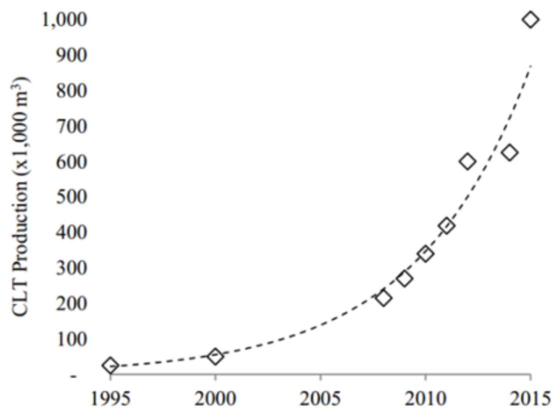


Fig. 2 Global production of CLT (Espinoza, Rodriguez Trujillo et al. 2015)

Top manufactures in Europe and the amount of their production in 2016 are listed in **Fehler! Verweisquelle konnte nicht gefunden werden.**.The produced CLT panels either are utilized in Europe or exported to the other countries.

Table 1. European manufacturers of CLT and the production capacity.

Product	Manufacturer	(1000) m3
Binderholz BBS 125	Binderholz Bausysteme GmbH	[1]200
Stora Enso CLT	Stora Enso Timber Bad St. Leonhard GmbH	[2]150
KLH-Massivholzplatte	KLH Massivholz GmbH	[3]125
MM - BSP	Mayr-Melnhof Holz Gaishorn GmbH	[4]70

1- https://www.binderholz.com/en/service-contact/news/details/press-release-binderholz-clt-bbs-extends-its-capacity/
2- http://www.storaenso.com/about/mills-capacities
3- http://www.mm-holz.com/en/company/locations/timber-processing-division/mm-holz-gaishorn/
4- http://bct.eco.umass.edu/wp-content/uploads/2014/10/KLH_Company-presentation_UMass-Amherst.pdf

A number of factors have contributed to current interest amongst construction professionals in the use of cross-laminated timber. Amongst these factors, enhanced mechanical properties (Silva, Branco et al. 2013), the interest of designers for a low-carbon building material for reducing the atmospheric carbon emission , higher value product of CLT from lower value timbers produced from fast grown and small diameters trees and stimulation of rural economy that rely on forest products are main reasons of the increasing interest in CLT (Podesto and Breneman 2016). Also CLT construction has important construction benefits such as (Wilson and Taylor 2010, Brandner 2013):

- Speed of construction and short erection times
- On site Accuracy of construction
- Simple connections
- Dry and clean construction techniques
- Reduced foundations requirements

Ease, speed, accuracy and simplicity of construction are associated with timber easy handling and prefabrication allowing a significant reduction of construction time, simplification of the site apparatus and also an increase of the on-site safety. A study showed that the cost of an 8- story building with a two-story concrete platform would be four percent less than a 10-story concrete building (Andrews 2016).

Other provisions can be counted as:

CLT panels are typically used as load-carrying plate elements in structural systems such as walls, floors and roofs (Mohammad, Gagnon et al. 2012). Crossing of the layers provides higher strength and stiffness properties to CLT panels in their both directions, this property makes it possible to take up forces in-plane as well as perpendicular to the plane (Silva, Branco et al. 2013). Therefore, CLT panels are able to be used as shear walls and floor and roof slabs as well.

An effective lateral load resisting system is provided in CLT panels due to the dimensional stability and rigidity. For assembling of the CLT structures multiple small connectors are used which provides the ductile behavior and energy dissipation in the final structure. Different studies on seismic performance of CLT structures, especially in multi-story buildings revealed no residual deformations.

Even though the fire resistance of CLT is dependent on the type of applied adhesive, different studies showed that because of slow charring of thick outer layers which protects the rest of panel from further degradation, valuable fire resistance is provides in thick cross section.

Thermal conductivity, which is the measure of the rate of heat flow through thickness of material, is much less in CLT panels than metals used in the buildings. Higher R-value of wood material comparing to steel and concrete resulted in much higher thermal conductivity (Rethinkwood, 2013).

Advantages of mid-rise wood construction

In case of construction in a region with poor soil condition (strength) wooden mid-rise buildings because of the lighter weight are better option.

Lighter weight of wooden structures will require less ground preparation and as a consequence more economical foundation, as well.

Wooden mid-rise building could be constructed out of prefabricated units and assembled at the job site, therefore the amount of onsite work and construction time will be reduced significantly (2016).

International Building Code (IBC) allows five stories of wood-frame construction in building occupancies that include multi-family, military, senior, student and affordable housing—and six stories for business (Sargent 2015). Multi story CLT building design is according to Eurocode in Europe and ANSI in US (American National Standard Institute).

Design Process

In general six steps were chosen to split the design process of a structure into a logical sequence from early scheme design consideration through to detailed design (Steelconstruction.info) (Fig. 3). In multi-story buildings, the design of the primary structure is strongly influenced by many other issues. In reality, building design is a synthesis of architectural, structural, services, logistics and buildability issues. The focal point of this project is working on the structural design of the buildings.

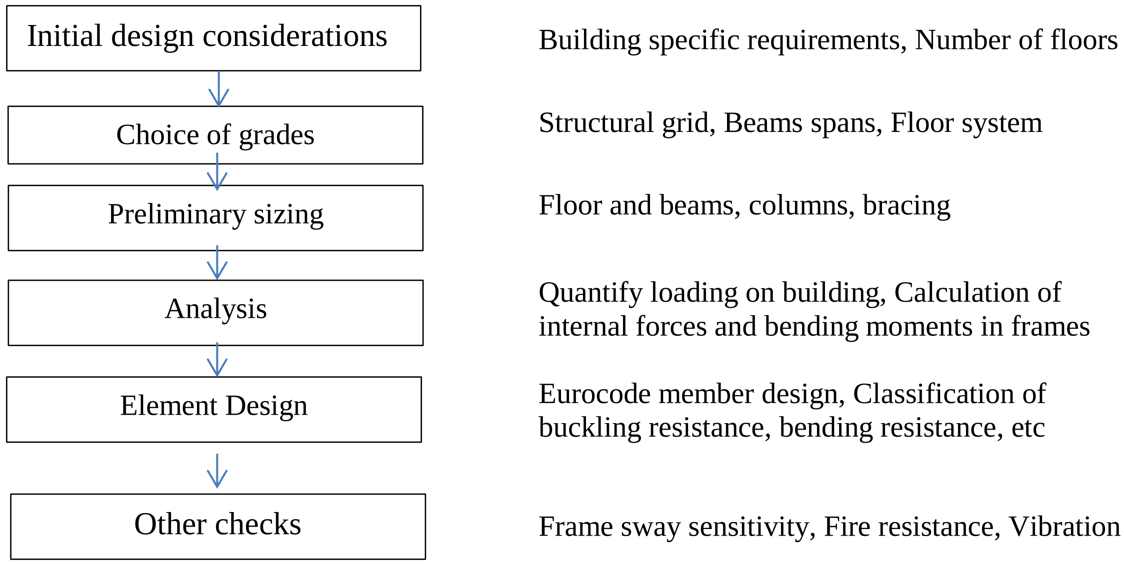


Fig. 3 The general design process of a buildings

Methodology

From the six steps mentioned in methodological part, according to the defined objective, this project focused on four later steps which are related to the structural analysis and also included the load sheet and load combinations, different limit states according to the Eurocode, roof system design (roof slabs, beams and girders), floor system design (floor slabs, beams and girders), braced frame design (columns and bracing) and also design of the gravity columns and connection designs and also final drawing of the buildings. CLT panels have the ability of self-bracing, therefore bracing was not considered in design of the building.

The drawing of the building includes cross section drawing of the building elevation, walls, floors, floor plan and other parts using drawing software.

According to the described different parts of this research project activity scheduled as below:

1. Evaluation of applied loads
2. Governing load combinations
3. Cross section drawing
4. Floor and roof slabs design
5. Visualization of floor plan in software

6. Design of shear walls
7. Design of connections
8. Presentation of detailed calculations and final result drawings.
9. Preparing of final research report

The 3d building drawings and preparation of the floor plan have been done in Revit software and for the component drawing the CLT engineer software was used. The designed building is assumed as a six-story building composed of a reinforced concrete ground level.

After preparing the building plan, the whole designing process has been conducted using CLT Engineer software (StoraEnso 2016). The CLT engineer is an online software and can be accessed through the internet.

The main component of building stories is assumed Austrian Pine CLT panels manufactured in Estora Enso Company, Austria and the related values were considered in design process. The Detail of the production is presented in Table 2.

Table 2 General properties of cross laminated panels produced in Stora Enso company (EstoraEnso 2015)

Structure	At least 3 layers (layers arranged perpendicular to each other with 3, 5 and 7 layers
Thickness	42-350 mm
Width* Length	Max 3.0*16.5 m
Classes of utilization	1 and 2
Wood species	Spruce, Fir, Pine, Larch
Adhesive	Type I Poly Urethane

Total length of the building is 24 m, the width is 16 m and the total height is 20 m. The total CLT floor area is 1920 square meter. In order to provide more support, in the floors four steel beam is considered in each floor design. The plan view of the first story of the building and the 3D view of the structure are shown in Fig. 4 and Fig. 5.

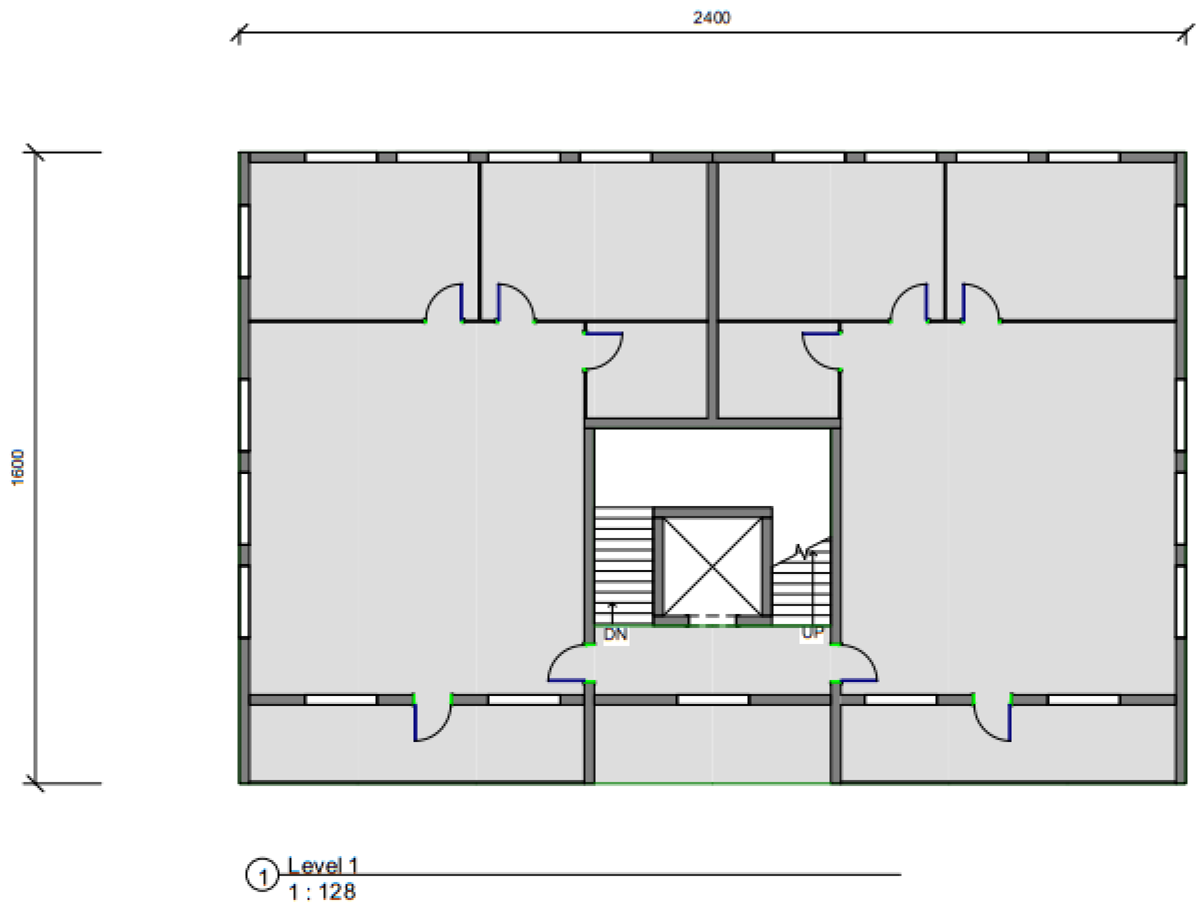


Fig. 4. Plan view of the first story of the building.

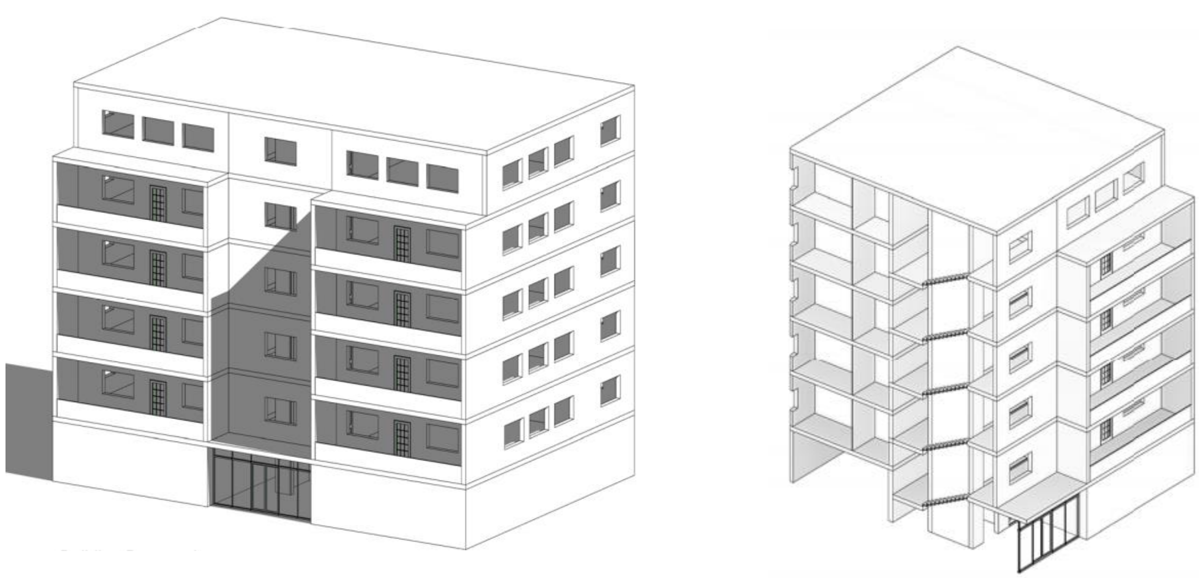


Fig. 5. 3D view and cross section of the building.

Evaluation of applied loads

Characteristic value of snow load and wind load in Salzburg area were obtained from Dlubal website (Dlubal n.a). Snow load is according to ÖNORM B 1991-1-3 and EN 1991-1-3 is 1.74 kN/m2, wind load is according to ÖNORM B 1991-1-4 and EN 1991-1-4 is 0.39 kN/m2 (1998-1:2011-06-15) and EN 1998-1.

Basic components of a CLT building

Fig. 6 presented the basic components of a multistory CLT building. As it is shown CLT panels could be applied in different part of the structure such as floor, roof, load bearing walls, non-load bearing walls, stairs and elevator shafts.

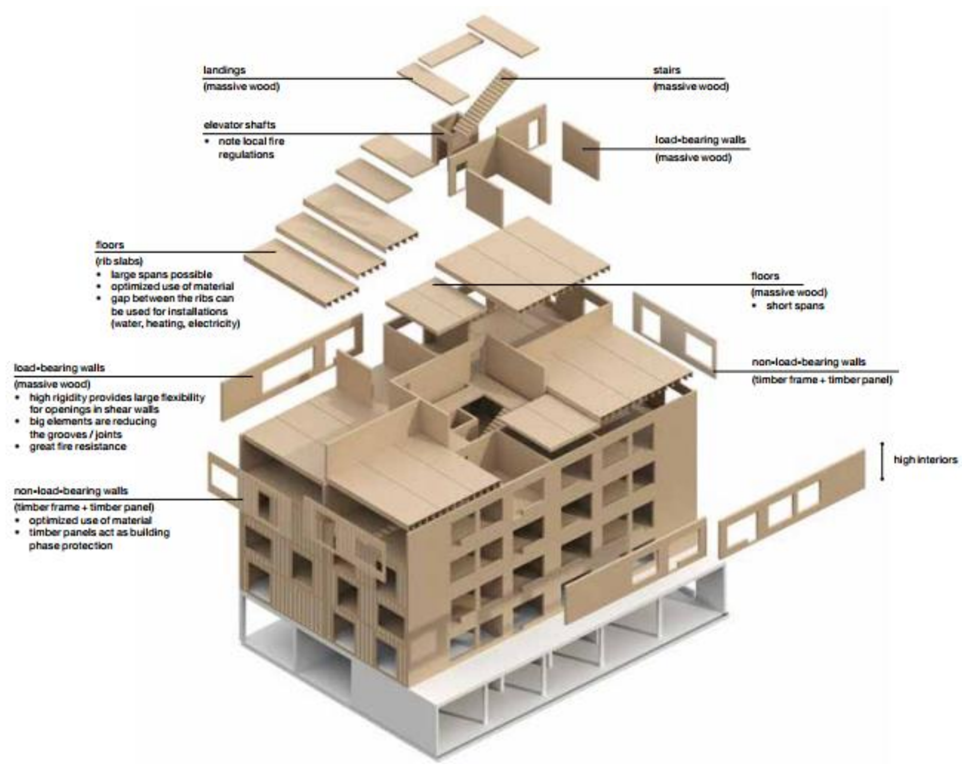


Fig. 6 Application of CLT panels for different component of a multistory building (StoraEnso 2016).

Some possible types of components which have been considered in designing the mid-rise building are explained in the following. Wall members are external wall, internal wall and compartment walls. External walls are covered with cladding or façade system from outside and are equipped with fire resistant and insulation layers. Compartment walls are fire resistance wall inside the buildings which are used for separating different areas of the building and insure the fire resistance. Internal walls are usually the non-loadbearing walls and used as partitions. The compartment floor with cement screed was regarded for the floor design

Wall components

External wall

Cross section configuration and 3D view of external wall is shown in Fig. 7. The considered external wall was covered on the inner side with one layer of 12.5 mm type F gypsum plasterboard, a 50 mm cavity for installations and on the external side with 20 mm of larch wood external wall cladding. The total thickness of layers D, E, F, G is 336.5 mm. External wall component properties is explained in Table 3 and the details of layers D-G which are thickness, fire and acoustic performance, is presented in Table 4.

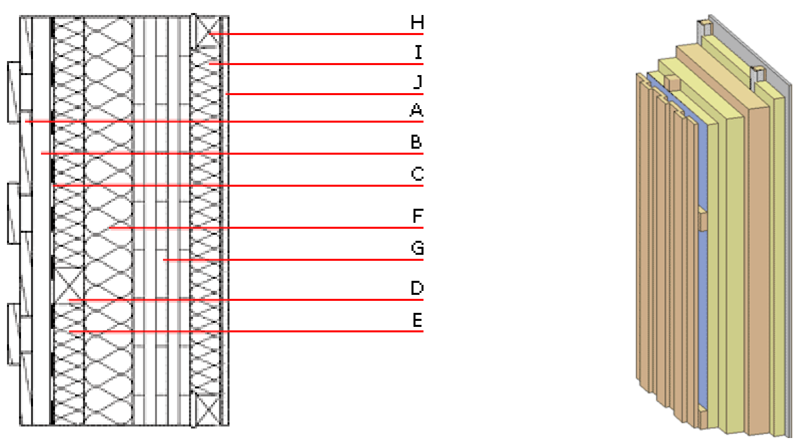


Fig. 7 Cross-section of standard configuration and 3D view for external wall (dataholz.com 2017)

Table 3. External wall component properties, (from outside to inside) (dataholz.com 2017)

Layer	Thickness mm	Building material	λ	μ min - max	ρ	c	Reaction to fire EN
A	20.0	larch wood external wall cladding	0,155	50	600	1,600	D
B	30.0	spruce wood battens (30/60)	0,120	50	450	1,600	D
C		vapour-permeable membrane sd ≤ 0,3m					
D	*	spruce wood battens (40/50 or 80/60;e=625)	0,120	50	450	1,600	D
E	*	Insulation material					
F	*	Insulation material					
G	*	solid wood (e.g. cross laminated timber)	0,130	50	500	1,600	D
H	50.0	spruce wood battens (40/50; e=625) mounted on resilient clips	0,120	50	450	1,600	D
I	50.0	Exchangeable layer					
J	12.5	gypsum plasterboards with improved properties at high temperatures (fire) or	0,250	10	800	1,050	A2
J	12.5	gypsum fibre board	0,320	21	1000	1,100	A2

λ: thermal conductivity [W/mK], μ: water vapor resistance factor, ρ: density [kg/m³], c:specific heat capacity [kJ/kgK].

Table 4. Detail properties of the external wall components (dataholz.com 2017)

Thickness of the layers (mm)					Fire Performance	Thermal properties			Acoustic performance	Eco Sustainability	Mass
D*	E*	F*	G*	Σ	REI	U [W/(m²K)]	$m_{w,B,A}$ [kg/m²]	Diffusion	Rw(C,Ctr)	$OI3_{Kon}$	M [kg/m²]
0,0	50,0	80,0	94,0	336,5	90	0,19	16,6	adequate	51	1,1	71,8

$OI3_{Kon}$ Is the ecological index which is ranged between -30 to 120. The higher the rate the ecological impact is more.

As it is shown in Fig. 8 is presented cross-section configuration and 3D view of a typical internal wall. Layers A and C are composed of two 12.5 mm gypsum plaster board or fiber board and layer B is a five layer CLT panel at the middle. Properties of different layers in external wall which are thermal conductivity, water vapor resistance factor, density and specific heat capacity and the details of layers are explained in Table 5.

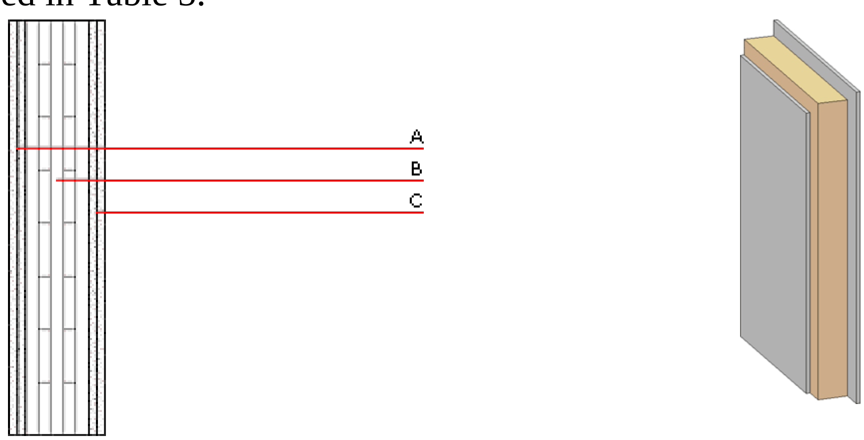


Fig. 8. Cross-section of standard configuration and 3D view for fire resistant internal wall (dataholz.com 2017)

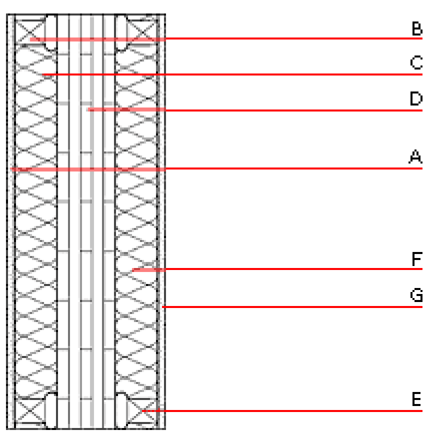
Table 5. Internal wall component properties, (from outside to inside, dimensions in mm) (dataholz.com 2017)

Layer	Thickness	Building material	λ	μ min - max	ρ	c	Reaction to fire EN
A	25.0	gypsum plasterboards with improved properties at high temperatures (fire) (2x12,5 mm) or	0,250	10	800	1,050	A2
A	25.0	gypsum fibre board (2x12,5 mm)	0,320	21	1000	1,100	A2
B	78.0	solid wood (e.g. cross laminated timer: thickness ≥ 78mm; 3-ply at least, surface layer at least 25mm)	0,130	50	500	1,600	D
C	25.0	gypsum plasterboards with improved properties at high temperatures (fire) (2x12,5 mm) or	0,250	10	800	1,050	A2
C	25.0	gypsum fibre board (2x12,5 mm)	0,320	21	1000	1,100	A2

λ: thermal conductivity [W/mK], μ: water vapor resistance factor, ρ: density [kg/m³], c:specific heat capacity [kJ/kgK].

Compartment wall

In Fig. 9 Cross-section configuration and 3D view of compartment wall is shown. Layers A and G are composed of a 12.5 mm gypsum plaster board or fiber board and layers B and F are layers with insulation materials with a five layer CLT panel at the middle. Thermal, vapor resistance and density of different wall layers is listed in Table 6. The total thickness of layers B and F together is 262 mm. Detail properties of these two layers are explained in Table 7.



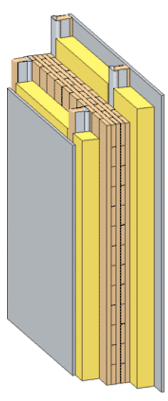


Fig. 9 Cross-section configuration and 3D view of compartment wall (dataholz.com 2017).

Table 6. Compartment wall component properties, (from outside to inside, dimensions in mm) (dataholz.com 2017)

Layer	Thickness	Building material	λ	μ min - max	ρ	c	Reaction to fire EN
A	12.5	gypsum plasterboards with improved properties at high temperatures (fire) or	0,250	10	800	1,050	A2
A	12.5	gypsum fibre board	0,320	21	1000	1,100	A2
B	*	Insulation material					
C	70.0	spruce wood batten mounted on resilient clips	0,120	50	450	1,600	D
D	95.0	solid wood (e.g. cross laminated timber)	0,130	50	500	1,600	D
E	70.0	spruce wood batten mounted on resilient clips	0,120	50	450	1,600	D
F	*	Insulation material					
G	12.5	gypsum plasterboards with improved properties at high temperatures (fire) or	0,250	10	800	1,050	A2
G	12.5	gypsum fibre board	0,320	21	1000	1,100	A2

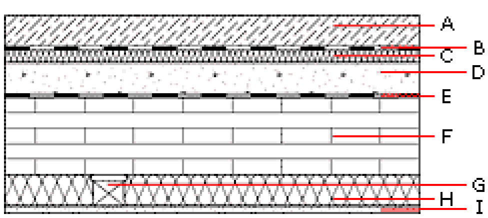
λ: thermal conductivity [W/mK], μ: water vapor resistance factor, ρ: density [kg/m³], c:specific heat capacity [kJ/kgK].

Table 7. Detail properties of the compartment wall components (dataholz.com 2017)

Thickness of the layers (mm)			Fire Performance	Thermal properties			Acoustic performance	Eco Sustainability	Mass
B*	F*	Σ	REI	U [W/(m²K)]	$m_{w,B,A}$ [kg/m²]	Diffusion	Rw(C,Ctr)	$OI3_{Kon}$	M [kg/m²]
60,0	60,0	262	90	0,25	15,7	adequate	57	-11,0	74,9

Compartment floor

Cross-section configuration and 3D view of the wall is shown in Fig. 10. The compartment floor is composed of a 50 mm cement screed top layer, a 40 mm of sound absorbing layer, a 40 mm of filling layer, 50 mm of glass wool a 12.5 mm of gypsum board and a 5 layer CLT panel. Property of different layers is listed in Table 8.



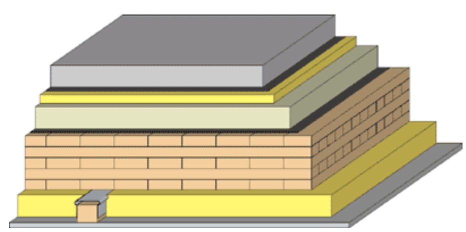


Fig. 10 Cross-section of standard configuration and 3D view of compartment floor (dataholz.com 2017).

Table 8 . Compartment floor component properties, (from top to bottom) (dataholz.com 2017)

Layer	**Thickness mm**	**Building material**	**λ**	**μ min - max**	**ρ**	**c**	**Reaction to fire EN**
A	50,0	cement screed or anhydrite screed	1,330	50 - 100	2000	1,080	A1
B		plastic separation layer	0,200	100000	1400	1,400	E
C	40,0	impact sound absorbing subflooring MW-T	0,035	1	68	1,030	A1
D	50,0	fill	0,700	1	1800	1,000	A1
E		trickling protection					E
F	134,0	solid wood (e.g. cross laminated timber); ≥ 134,0; at least 5-layers, top layer at least 26 mm)	0,130	50	500	1,600	D
G	70,0	spruce wood battens (40/50) mounted on resilient clips	0,120	50	450	1,600	D
H	50,0	glass wool [0,0040; R=16]	0,040	1	16	1,030	A1
I	12,5	gypsum plasterboards with improved properties at high temperatures (fire) or	0,250	10	800	1,050	A2
I	12,5	gypsum fibre board	0,320	21	1000	1,100	A2

λ: thermal conductivity [W/mK], μ: water vapor resistance factor, ρ: density [kg/m³], c:specific heat capacity [kJ/kgK].

Design basics

In designing CLT member the cross laminating nature of panels should be taken in to account. That means some layers are in the longitudinal direction (machine direction) and some are cross wise to the longitudinal direction. The cross wise layers are weaker, but they still have some effects on the mechanical properties and internal stresses. The effect of cross layers is considered in different analysis methods for CLT design such as the Modified Gamma Theory, the Shear Analogy, Timoshenko Theory and Finite Element Analysis. The CLT engineer software designed by Stora Enso company is based on Timoshenko Theory (StoraEnso 2016).

Fire design

The fire design is being executed according to EN1995-1-2 and its national annexes. As alternative, fire design (determination of the residual timber section) according to the guideline Fire Safety in Timber Buildings is also provided in the software.

Fire resistance classes according to Eurocode are listed in Table 9 Classification is according to the length of time the structural ability can be maintained and called the fire resistance duration. According to the table, the range of the resistance duration is 30 to 180 minute.

Table 9. Resistant to fire classification according to European standard (EN13501-2 2016)

Class	Resistance to fire (Minute)
REI 30	≥ 30
REI 60	≥ 60
REI 90	≥ 90
REI 120	≥ 120
REI 180	≥180

Higher fire resistance of CLT component can be achieved with multiple layer CLT elements. For instance, for a three-layer CLT panel without any cladding, the obtained fire resistance is REI 60 and adding a single layer of plasterboard, the fire resistance would increase up to REI 90. Practically, increased fire resistance can be attained by increasing the thickness of the CLT panel, Increasing the number of layers of the CLT element or applying the fire resistant cladding (Golger 2014).

The fire resistance for CLT panels in the software is listed up to 120 min which R90 with 90 min of resistance to the fire is selected for panels in this design procedure. Load combination factor for fire design was considered as Ψ_2. For fire protection there are different options of single or double ply cladding provided in the CLT Engineer software. Single ply 12.5 plasterboard was considered for fire protection cladding.

Service classes

According to Eurocode there are three service classes defined for environmental conditions as is shown in Table 10. Service classes 1 and 2 are permitted for Stora Enso panels. Class three is for moisture amount of more than 20 percent and relative humidity of more than 80 % and is not allowed. Class 2 is selected conservatively through the design process (EN1995-1-1 2004).

Table 10 Service classes according to Eurocode (EN1995-1-1 2004)

Service class	Average amount of moisture content (%)	Defined environmental conditions
1	≤ 12	20°C and % 65 relative humidity
2	≤ 20	20°C and % 85 relative humidity
3	> 20	Climatic conditions leading to higher moisture contents than in service class 2

Vibration analysis

For the vibration analysis of the floor system, the tributary area of each individual bay was entered. Properties of a five cm screed layer with the damping coefficient of 0.04 and young modulus of 26000 N/mm^2 was added for vibration analysis.

Floor design

According to Stora Enso product information and design software, C24 pine 5 layers CLT panels with the thickness of 180 mm was sufficient for bearing the floor loads. Modulus of elasticity, bending and shear strength value of pine species used for the design process is listed in (Table 11) as mentioned in the design software. No edge gluing option was used for analysis. According to the place of floor panels some panels run perpendicular and some parallel to the span direction. The self-weight of panels was included in the calculation automatically in the software.

Table 11. Strength value of the pine used for the building design (StoraEnso 2016)

material	$f_{m,k}$	$f_{t,0,k}$	$f_{t,90,k}$	$f_{c,0,k}$	$f_{c,90,k}$	$f_{v,k}$	$f_{r,k\ min}$	$E_{0,mean}$	G_{mean}	$G_{r,mean}$
	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]
C24 pine	24.00	14.00	0.35	21.00	2.40	4.00	1.70	11,600.00	460.00	50.00

A sample sketch of floor system is provided in Fig. 11. It is part of the floor system with the spans of 2 m, 1.45 m and 0.55 m. and width of 3 meter with the direction of surface layers perpendicular to the support systems.

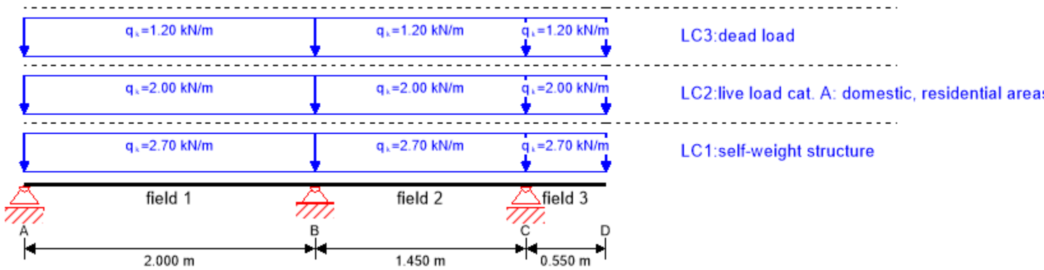


Fig. 11. Example sketch of a floor system as a continuous beam

For each step of analysis the software provides four different design ratios for the member. The best calculated ratio according to thickness of layers and assumed properties in the design process is shown, as well. For the example floor shown in Fig. 11 the ratios are as 21 %, 41 %, 34 % and 29 % for CLT 180 L5s, CLT 140 L5s – 2, 34 % CLT 240 L7s - 2 and 29 % CLT 160 L5s, respectively. Ratios above 100% are an indication of member overloading. According to suggested calculations and thickness of the other panels of the floor system a 3 m by 4 m CLT 180 L5s was selected for the specified part of floor. Thickness of the layers and the profile properties of the five layer CLT panel with the thickness of 180 cm are presented in Table 12.

Table 12. Properties of the example CLT panel

layer	thickness	type	material
1	40.0 mm	L	C24 pine
2	30.0 mm	C	C24 pine
3	40.0 mm	L	C24 pine
4	30.0 mm	C	C24 pine
5	40.0 mm	L	C24 pine

L:Longitudinal layer, C: Crossed layer

Design for Ultimate limit state

Ultimate limit state calculations were based on out of plan flexural properties, shear properties and rolling shear properties.
Some details of the calculation of example floor beam which was part of the software calculation are presented below. Shown in Fig. 12, the maximum shear force in this

example was – 6.14 kN and maximum moment was 1.83 kN.m. Ultimate limit states design results are shown in Table 13 ,Table **14** and 15.

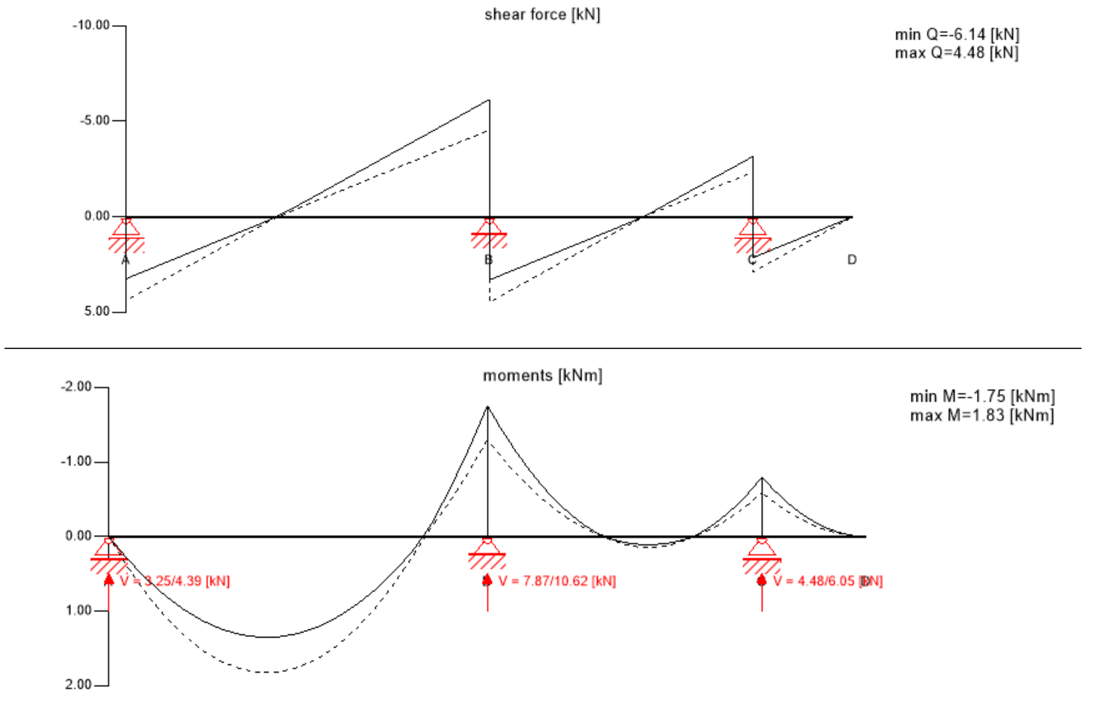


Fig. 12 Static analysis for hear (top) and moment (bottom) diagram of the example floor beam. Result of load combination.

Table 13 presented flexural design properties of example floor. Out of plane bending strength is 24 N/mm^2 and bending stress is 2.33 N/mm^2. The ratio of design bending stress to design bending strength should be equal to or less than 1.0 which here it is obtained as 0.02 and 0.04.

Table 13. Flexural design properties of the example floor beam

Span	$\mathbf{f_{m,k}}$	γ_m	$\mathbf{k_{mod}}$	$\mathbf{k_{sys}}$	$\mathbf{f_{m,d}}$	$\mathbf{M_d}$	$\sigma_{m,d}$	**Ratio**
	[N/mm²]	[-]	[-]	[-]	[N/mm²]	[kNm]	[N/mm²]	%
First	24.00	1.25	0.80	1.10	16.90	2.98	0.64	4
Second	24.00	1.25	0.80	1.10	16.90	-2.80	0.60	4
Third	24.00	1.25	0.80	1.10	16.90	-1.25	0.27	2

$\mathbf{f_{m,k}}$: Characteristic out of plan bending strength, γ_m: partial safety factor (is 1.25 in Austria), $\mathbf{k_{mod}}$: modification factor, $\mathbf{f_{m,d}}$: Design bending stress $\mathbf{M_d}$: design moment, $\sigma_{m,d}$: maximum design bending stress on the edge.

Longitudinal layers shear analysis of the example floor beam is shown in Table 14. Longitudinal out of plan shear strength is 4 N/mm^2, design shear strength of the longitudinal layer is 2.56 N/mm^2 and longitudinal shear stress is 0.02-0.04N/mm^2. The ratio of design shear stress to design shear strength should be equal to or less than 1.0 which is 0.01 to 0.02.

Table 14. Shear analysis of longitudinal layers in the example floor beam

Span	$\mathbf{f_{v,k}}$	γ_m	$\mathbf{k_{mod}}$	$\mathbf{f_{v,d}}$	$\mathbf{V_d}$	$\tau_{v,d}$	**ratio**
	[N/mm²]	[-]	[-]	[N/mm²]	[kN]	[N/mm²]	%
First	4.00	1.25	0.80	2.56	9.67	0.04	2
Second	4.00	1.25	0.80	2.56	7.38	0.03	1
Third	4.00	1.25	0.80	2.56	4.55	0.02	1

$\mathbf{f_{v,k}}$: longitudinal out of plan shear strength, γ_m: partial safety factor (is 1.25 in Austria), $\mathbf{k_{mod}}$: modification factor, $\mathbf{f_{v,d}}$: Design shear strength of the longitudinal layer, $\mathbf{V_d}$: design shear force, $\tau_{v,d}$: shear stress of the longitudinal layer

Analysis for rolling shear or shear properties for transverse layers is shown in Table 15. Out of plan rolling shear strength is 1.23 N/mm^2 and rolling shear stress is 0.04 N/mm^2. The ratio of shear stress and design shear stress of the transverse layers should be equal or less than 1 which is 0.03 to 0.06 for different spans of for this floor panel.

Table 15. Rolling shear analysis of the example floor beam

Span	$\mathbf{f_{r,k}}$	γ_m	$\mathbf{k_{mod}}$	$\mathbf{f_{r,d}}$	$\mathbf{V_d}$	$\tau_{r,d}$	**Ratio**
	[N/mm²]	[-]	[-]	[N/mm²]	[kN]	[N/mm²]	%
First	1.23	1.25	0.80	0.78	9.67	0.04	6
Second	1.23	1.25	0.80	0.78	7.38	0.03	4
Third	1.23	1.25	0.80	0.78	4.55	0.02	3

$\mathbf{f_{r,k}}$: Out-of-plane rolling shear strength, γ_m: Martial safety factor, $\mathbf{k_{mod}}$: Modification factor, $\mathbf{f_{r,d}}$: rolling shear strength of the transverse layer, $\mathbf{V_d}$: design shear force, $\tau_{r,d}$: shear stress of the transverse layers

Ratio calculation shows that flexural, longitudinal and rolling shear, respectively are using % 4, % 2 and % 6 of the design capacity. Therefore, rolling shear properties were the controlling value of the ultimate limit state.

Flexural, shear and rolling shear stresses diagrams and their maximum values of 0.64, 0.04 and 0.04 N/mm^2 are shown in Fig. 13.

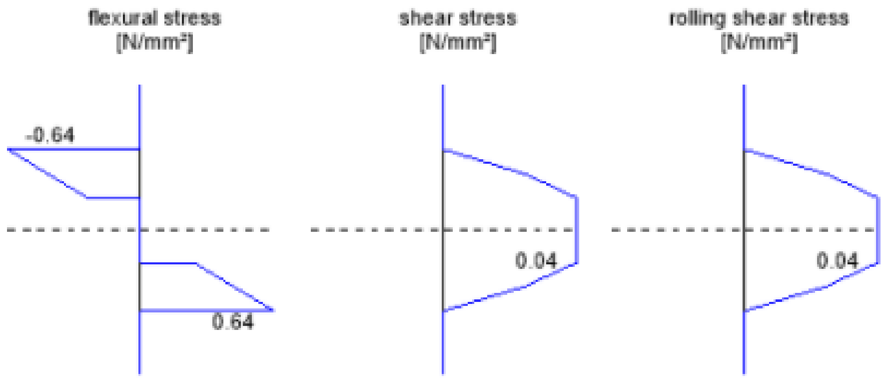


Fig. 13. Flexural stress, shear stress and rolling shear stress diagrams of the example floor beam

Ultimate limit state of fire design

Ultimate limit state calculations for fire were based on out of plan flexural properties, shear properties and rolling shear properties, as well. Ultimate limit states design results are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**Table 17 and 18.

Flexural design properties of example floor Shown in Table 16 are out of plane bending strength with the value of 24 N/mm^2 and maximum bending stress of 3.72 N/mm^2. The design ratio is 0.05 to 0.12 percent.

Table 16. Flexural properties for fire design of the example floor beam

Span	$\mathbf{f_{m,k}}$	$\boldsymbol{\gamma_m}$	$\mathbf{k_{mod}}$	$\mathbf{K_{fire}}$	$\mathbf{f_{m,d}}$	$\mathbf{M_d}$	$\boldsymbol{\sigma_{m,d}}$	**Ratio**
	[N/mm²]	[-]	[-]	[-]	[N/mm²]	[kNm]	[N/mm²]	%
First	24.00	1.25	1.00	1.15	30.36	-1.67	3.72	12
Second	24.00	1.25	1.00	1.15	30.36	-1.67	3.72	12
Third	24.00	1.25	1.00	1.15	30.36	-0.68	1.51	5

$\mathbf{f_{m,k}}$: Characteristic out of plan bending strength, $\boldsymbol{\gamma_m}$: partial safety factor (is 1.25 in Austria), $\mathbf{k_{mod}}$: modification factor, $\mathbf{f_{m,d}}$: Design bending stress $\mathbf{M_d}$: design moment, $\boldsymbol{\sigma_{m,d}}$: maximum design bending stress on the edge.

Fire design shear analysis of longitudinal layers of the example floor beam is shown in Table 17. Design shear strength of the longitudinal layer is 5.34 N/mm^2 and longitudinal shear stress is 0.04 - 0.09 N/mm^2. The design shear ratio for fire is 0.01 to 0.02.

Table 17. Shear analysis of fire design of the example floor beam

Span	$\mathbf{f_{v,k}}$	$\boldsymbol{\gamma_m}$	$\mathbf{k_{mod}}$	$\mathbf{f_{v,d}}$	$\mathbf{V_d}$	$\boldsymbol{\tau_{v,d}}$	**ratio**
	[N/mm²]	[-]	[-]	[N/mm²]	[kN]	[N/mm²]	%
First	4.00	1.25	1.00	4.60	5.34	0.09	2
Second	4.00	1.25	1.00	4.60	4.01	0.07	1
Third	4.00	1.25	1.00	4.60	2.48	0.04	1

$\mathbf{f_{v,k}}$: longitudinal out of plan shear strength, $\boldsymbol{\gamma_m}$: partial safety factor (is 1.25 in Austria), $\mathbf{k_{mod}}$: modification factor, $\mathbf{f_{v,d}}$: Design shear strength of the longitudinal layer, $\mathbf{V_d}$: design shear force, $\boldsymbol{\tau_{v,d}}$: shear stress of the longitudinal layer

Shown in Table 18, Out of plan rolling shear strength is calculated as 1.23 N/mm^2. Maximum design rolling shear stress for fire is 0.03 N/mm^2 and design rolling shear ratio for fire is 0.04 which is less than 1.

Table 18. Rolling shear analysis of fire design of the example floor beam

Span	$\mathbf{f_{r,k}}$	$\boldsymbol{\gamma_m}$	$\mathbf{k_{mod}}$	$\mathbf{f_{r,d}}$	$\mathbf{V_d}$	$\boldsymbol{\tau_{r,d}}$	**Ratio**
	[N/mm²]	[-]	[-]	[N/mm²]	[kN]	[N/mm²]	%
First	1.23	1.25	1.00	1.41	5.34	0.00	0
Second	1.23	1.25	0.80	0.78	7.38	0.03	4
Third	1.23	1.25	0.80	0.78	4.55	0.02	3

$\mathbf{f_{r,k}}$: Out-of-plane rolling shear strength, $\boldsymbol{\gamma_m}$: Martial safety factor, $\mathbf{k_{mod}}$: Modification factor, $\mathbf{f_{r,d}}$: rolling shear strength of the transverse layer, $\mathbf{V_d}$: design shear force, $\boldsymbol{\tau_{r,d}}$: shear stress of the transverse layers

Design for service limit state

Service limit states (SLS) for initial or instantaneous deflection due to permanent and variable loads, final deflection (instantaneous deflection and deflection due to creep) and net final deflection (final deflection plus creep deflection) were considered as L/300, L/150 and L/250 mm, respectively.

The design value calculated by software for these limit states is presented in Table 19. The maximum amount of initial deflection is 0.5 mm which is lower than the limit state of 6.7 mm. Maximum Final deflection and net final deflection are calculated as 0.8 mm and 0.6 mm which are less than the calculated limit states of 13.3 mm and 8.0

mm. Deflection factor is 1 and the maximum span length for the example floor is 2 meter.

Table 19. Maximum amount of Initial, final and net final deflection calculated for different spans of the example floor beam

Initial deflection	Final deflection	Net final deflection
[mm]	[mm]	[mm]
0.5	0.8	0.6
Initial, final and net final deflection limits are 6.7, 13.3 and 8.0 mm.		

Design for vibration

For vibration which is a controlling design value for floor system design, four criteria are defined in two classes I and II Table 20. Vibration design value calculated conservatively based on the class I criteria. The total design ratio obtained for vibration of the example floor was % 21.

Table 20. Vibration criteria and the value obtained for the example floor

Criterion	Class I	Class II	Calculated
Frequency criterion min [Hz]	4.50	4.50	38.11
Frequency criterion [Hz]	8.00	6.00	38.11
Acceleration criterion [m/s²]	0.05	0.10	0.0
Stiffness criterion [mm]	0.25	0.50	0.022

Final size of floor panels

The design calculation has been conducted with the same design consideration of ULS, ULS fire, SLS and vibration for the other floors. Number and size of the panels and direction of the surface layers are listed in Table 21.

Table 21. Size and the number of the panels used for the first floor

Amount of panel	Size (m^2)	Direction of surface layer with the span
8	2*6	Perpendicular
4	1.5*3	Perpendicular
20	1*9	Perpendicular
2 (just for the first floor)	3*4	Perpendicular
8	2*6	parallel
2	3*2	parallel

Flexural design properties for different floor panels

The summary of flexural design properties for the other floor panels is listed in Table 22. Percent of flexural design capacity usage is between 7-25 percent.

Table 22. Flexural design properties floor beam

Span	$f_{m,k}$	$f_{m,d}$	$\sigma_{m,d}$	Ratio
	[N/mm²]	[N/mm²]	[N/mm²]	%
1*9	24	12.67	3.13	25
1.5*3	24	16.90	1.07	6
2*6 (Perpendicular)	24	12.67	2.33	18
3*4	24	12.67	1.17	9
2*6 (Parallel)	24	12.67	2.33	18
3*2	24	12.67	0.84	7

The summary of shear analysis and rolling shear analysis for the other floor panels are shown in Table 23 and Table 24. Percent usage of Shear and rolling shear capacities are between 2-4 percent and 5-12 percent.

Table 23. Summary of shear analysis of longitudinal layers in floor beams

Span	$f_{v,k}$	$f_{v,d}$	$\tau_{v,d}$	Ratio
	[N/mm²]	[N/mm²]	[N/mm²]	%
1*9	4	1.92	0.13	2
1.5*3	4	2.56	0.05	2
2*6 (Perpendicular)	4	1.92	0.08	4
3*4	4	1.92	0.04	2
2*6 (Parallel)	4	1.92	0.08	4
3*2	4	1.92	0.04	2

Table 24. Summary of rolling shear analysis of the floor beams

Span	$\mathbf{f_{r,k}}$	$\mathbf{f_{r,d}}$	$\boldsymbol{\tau_{r,d}}$	**Ratio**
	[N/mm²]	[N/mm²]	[N/mm²]	%
1*9	1.23	0.59	0.13	6
1.5*3	1.42	3.91	0.04	5
2*6 (Perpendicular)	1.50	0.72	0.08	12
3*4	1.50	0.72	0.04	5
2*6 (Parallel)	1.50	0.72	0.08	12
3*2	1.60	0.77	0.03	5

Referring to Table 25 it is revealed that the controlling limit state is vibration, considering class I criteria conservatively. The maximum vibration capacity utilization is belong to floor panels with the length of 9 meter which spans three equal 3- meter spans.

Table 25. Summary of vibration analysis of the floor beams

Criterion	1*9	1.5*3	2*6 (Perpendicular)	3*4	2*6 (Parallel)	3*2
Frequency criterion [Hz]	8.123	28.851	38.11	15.088	23.791	23.791
Acceleration criterion [m/s²]	0.016	0	0.0	0.014	0	0
Stiffness criterion [mm]	0.149	0.053	0.022	0.063	0.032	0.032
Maximum utilization of vibration capacity %	98	28	77	53	34	34

Design of wall system

According to software analysis, C24 pine 5 layers CLT panels with the thickness of 200 mm was sufficient for designing of load bearing walls. CLT panel is composed of 5 equal thickness layers. Cross section profile property of wall panel is shown in Table 26. No edge gluing option was used for analysis. The entire load bearing panels considered with horizontal direction. The self-weight of panels was included in the calculation automatically in the software. Calculation is based on first CLT floor and self-weight of all upper floors is included as the dead load on the first floor wall system. Self-Wight of one floor is calculated as 5.85 kN/m.

Table 26 CLT section profile properties of panels used for wall system

layer	thickness	type	material
1	40.0 mm	L	C24 pine
2	40.0 mm	C	C24 pine
3	40.0 mm	L	C24 pine
4	40.0 mm	C	C24 pine
5	40.0 mm	L	C24 pine
L:Longitudinal layer, C: Crossed layer			

Plan view of 12 m wall with four window cut is shown in Fig. 14 Wall Type 1 with length of 12 meter. The direction of cover layers is parallel to the length of wall The calculated design ratios for different controlling limit states of ULS, fire ULS and SLS for 12 meter wall are %10, % 43 and % 3. Controlling property for ULS and for ULS fire is buckling. The values and model obtained for ULS and ULS fire from CLT designer software are shown in Table 27 and Table 28.

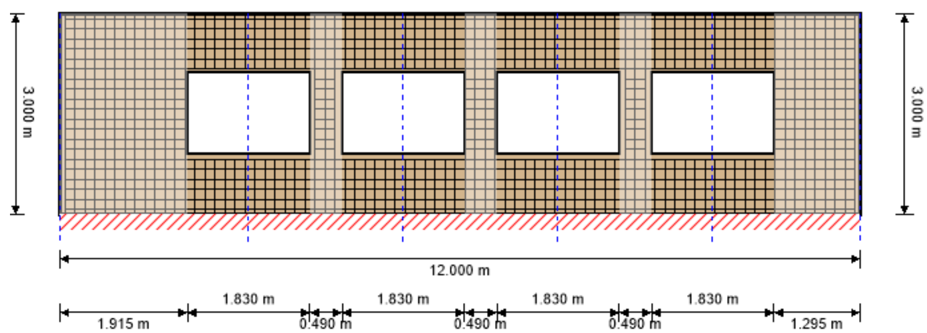
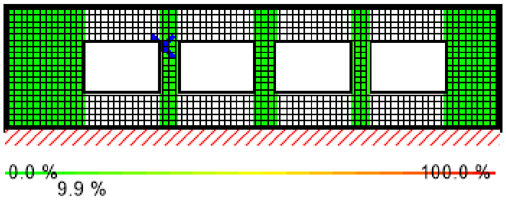


Fig. 14 Wall Type 1 with length of 12 meter. The direction of cover layers is parallel to the length of wall

Table 27 Maximum utilization rate for buckling of 12 meter wall.

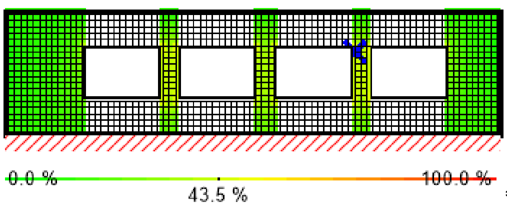
***Node$_{Id}$**	**X**	**Z**	**l_k**	**λ_y**	**βc**	**$k_{c,y}$**	**$f_{c,d}$**	**$\sigma_{c,0,d}$**	**$\sigma_{m,y,d}$**	**ratio**
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
1146	3.825	2.025	3.0	72	0.2	0.627	15.12	0.94	0.00	10



*Node with maximum utilization is shown in blue mark.

Table 28 Maximum fire utilization rate for buckling of 12 meter wall.

*Node$_{Id}$	X	Z	l_k	λ_y	β_c	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	ratio
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
1177	8.475	2.025	3.0	260	0.2	0.062	24.15	0.65	0.00	43



*Node with maximum utilization is shown in blue mark.

The calculated design ratios of ULS, fire ULS and SLS for 8.8 meter wall are %4, % 18 and % 1. The values and model for ULD of buckling and ULS fire are shown in Table 29 and Table 30.

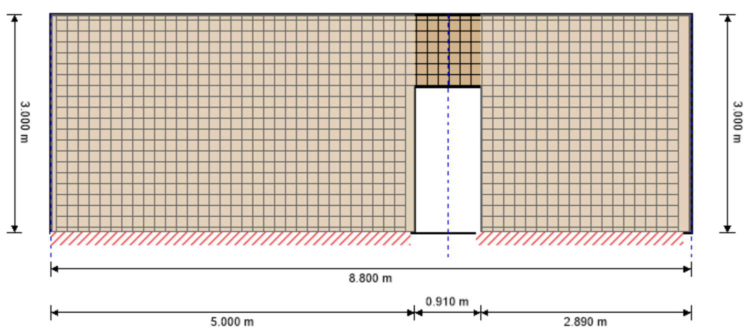
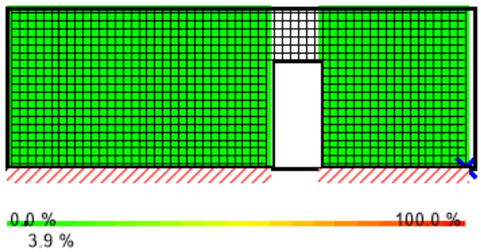


Fig. 15 Wall Type 2 with the length of 8.80 meter and one opening. The direction of cover layers is parallel to the length of wall.

Table 29. Maximum utilization rate for buckling for wall of 8.80 meter.

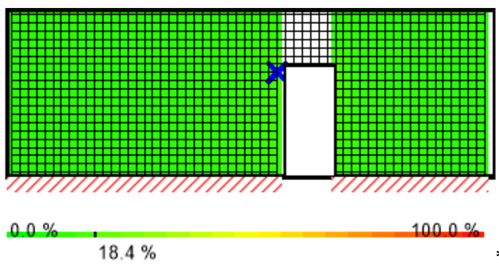
*Node$_{Id}$	X	Z	l_k	λ_y	βc	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	ratio
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
58	8.625	0	3.0	72	0.2	0.627	15.12	0.37	0.00	4



*Node with maximum utilization is shown in blue mark.

Table 30. Maximum fire utilization rate for buckling of 8.80 meter wall (18 %).

*Node$_{Id}$	X	Z	l_k	λ_y	β_c	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	ratio
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
787	4.875	1.875	3.0	260	0.2	0.062	24.15	0.28	0.00	18



*Node with maximum utilization is shown in blue mark.

Global utilization ratios of ULS, fire ULS and SLS of respectively % 8, % 38 and % 2, were obtained for 8.6 meter wall. The values and model obtained for ULD buckling and ULS fire buckling is shown in Table 31 and Table 32.

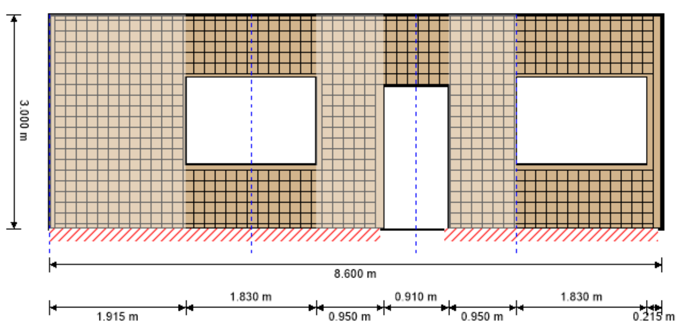
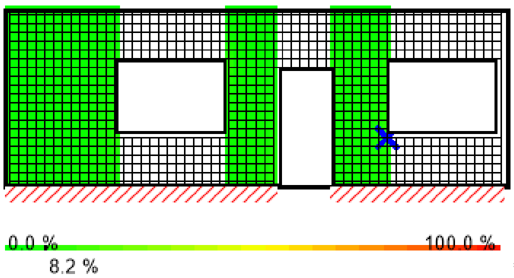


Fig. 16. Wall Type 3 with the length of 8.6 meter and three openings. The direction of cover layers is parallel to the length of wall

Table 31. Maximum utilization rate for buckling of 8.6 meter wall.

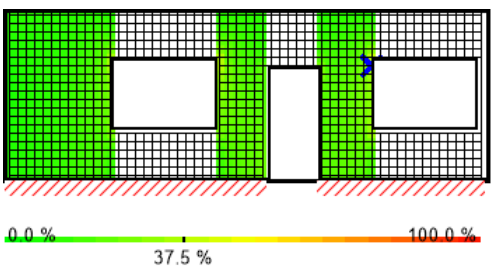
*Node$_{Id}$	X	Z	l_k	λ_y	βc	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	ratio
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
386	6.525	0.825	3.0	72	0.2	0.627	15.12	0.78	0.00	8



*Node with maximum utilization is shown in blue mark.

Table 32. Maximum fire utilization rate for buckling of 8.6 meter wall.

*Node$_{Id}$	X	Z	l_k	λ_y	β_c	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	ratio
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
842	6.525	2.025	3.0	260	0.2	0.062	24.15	0.56	0.00	38



*Node with maximum utilization is shown in blue mark.

The calculated design ratios of ULS, fire ULS and SLS for 8 meter wall are %11, % 73 and % 2. The values and model for ULD of buckling and ULS fire obtained from CLT designer software are shown in Table 33 and Table 34.

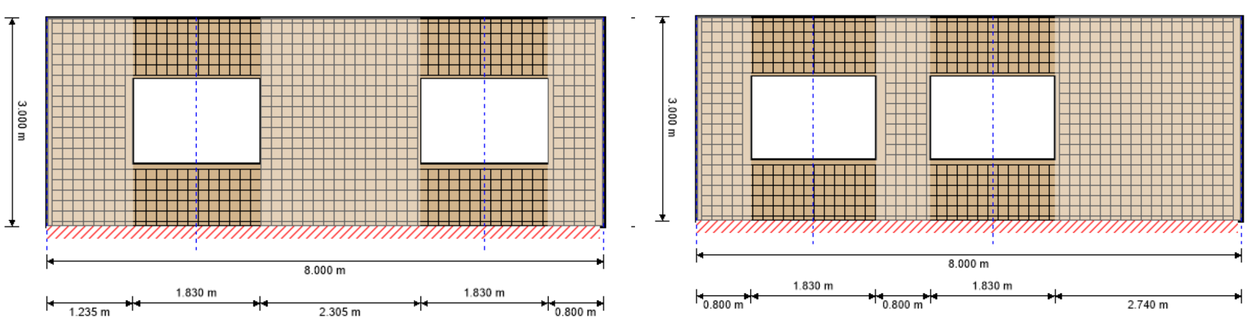
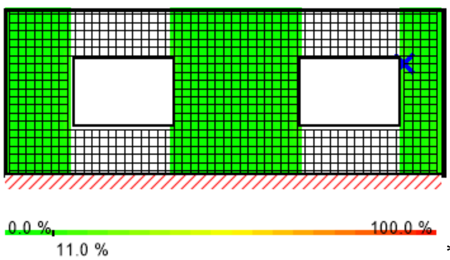


Fig. 17. Wall Type 4 (two configurations) with the length of 8 meter and two openings. The direction of cover layers is parallel to the length of wall

Table 33. Maximum utilization rate for buckling of 8 meter wall

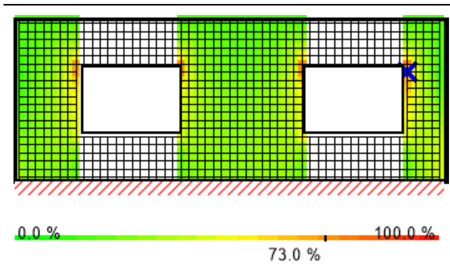
***Node**$_{Id}$	**X**	**Z**	l_k	λ_y	**βc**	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	**ratio**
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
791	7.275	2.025	3.0	83	0.2	0.511	15.12	0.85	0.00	11 %



*Node with maximum utilization is shown in blue mark.

Table 34. Maximum fire utilization rate for buckling of 8 meter wall

***Node**$_{Id}$	**X**	**Z**	l_k	λ_y	β_c	$k_{c,y}$	$f_{c,d}$	$\sigma_{c,0,d}$	$\sigma_{m,y,d}$	**ratio**
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
791	7.275	2.025	3.0	346	0.2	0.035	24.15	0.63	0.00	73 %



*Node with maximum utilization is shown in blue mark.

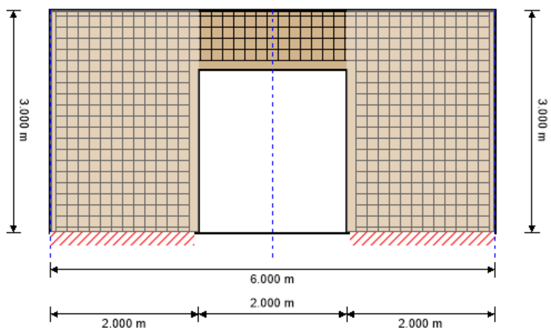
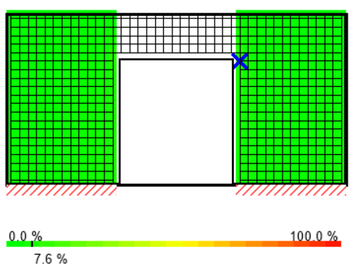


Fig. 18. Wall Type 5 (two configurations) with the length of 6 meter and one opening. The direction of cover layers is parallel to the length of wall

The calculated design ratios of ULS, fire ULS and SLS for 6 meter wall are %8, % 42 and % 2. The calculated values and model for ULD of buckling and ULS fire are shown in Table 35 and Table 36.

Table 35. Maximum utilization rate for buckling of 6 meter wall

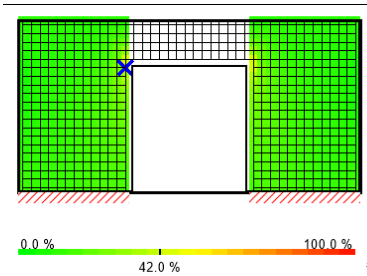
***Node$_{Id}$**	**X**	**Z**	**l_k**	**λ_y**	**βc**	**$k_{c,y}$**	**$f_{c,d}$**	**$\sigma_{c,0,d}$**	**$\sigma_{m,y,d}$**	**ratio**
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
628	4.125	2.175	3.0	72	0.2	0.627	15.12	0.72	0.00	8 %



*Node with maximum utilization is shown in blue mark.

Table 36. Maximum fire utilization rate for buckling of 8 meter wall

***Node$_{Id}$**	**X**	**Z**	**l_k**	**λ_y**	**β_c**	**$k_{c,y}$**	**$f_{c,d}$**	**$\sigma_{c,0,d}$**	**$\sigma_{m,y,d}$**	**ratio**
[-]	[m]	[m]	[m]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[N/mm²]	[%]
613	1.875	2.175	3.0	260	0.2	0.062	24.15	0.63	0.00	42 %



*Node with maximum utilization is shown in blue mark.

All the obtained design ratio values for the wall system are below the % 100 rate; there for all of the walls with the selected properties are adequate for bearing loads in the building.

Size and number of walls

The height of wall panels considered as 3 meter with both cover layers horizontally directed. Length and number of the wall panels used for the first floor is listed in Table 37.

Table 37. Size and the number of panels used for walls in first floor

Number of panels	Length (m)	Direction of surface layer
4	8	Horizontal
2	12	Horizontal
1	6.04	Horizontal
1	6	Horizontal
2	8.80	Horizontal
2	8.60	Horizontal

Consulting to the CLT producers, it is mentioned that for long distance shipping such as shipping to other countries or US; it is better to use smaller length of the panels for reducing shipping cost and more shipping flexibility.

CLT connection

Connection information was obtained from a visit to Rotho Blaas Company and also the company's catalogue. The most common connections employed in CLT building construction are angle brackets and perforated plates.

Angle brackets are utilized for shear and tensile connection of wooden walls to wooden substructures Fig. 19. Shear connection angle brackets are produced in two types with the height of 120 and 240 and width of 71 and 200 mm. Tensile angle brackets are introduced to the market in four different types with the heights of 340, 440 and 540 mm with the washer hole of 17 mm and 620 mm with the washer hole of 21 mm.

Shear brackets are designed to bear high shear stress resistance and angle brackets are designed for high tensile resistance. Both of these connectors are suitable for seismic areas applications, are reinforced for good torsional behavior and can reach the maximum performance using screw fastening.

Fig. 19.Shear (left) and tensile (right) angle brackets employed for wall to floor connections (Rotho Blaas catalogue).

Perforated plats are produced according to EN 14545 and are available in length up to 120 cm, width up to 40 cm and thickness up to 0.2 cm (Fig. 20).

Fig. 20. Perforated plates for wooden wall connection to substructures (other wooden walls or concrete fundation). Left form Rotho Blass catalogue, right photo credit to Ermanno Akler, Holzpak.

Recently an innovative connector called X-Rot is designed and produced in Rotho Blaas which is used in place of spline and screws for wall to wall connectors. However, Connector calculation is not performed in this project, because the lake of time and detail information.

Benefits/relevance/expected results

The process of designing mid-rise 6 story CLT building with the first concrete floor is presented in this report. Wall and floor systems were designed according to Eurocode and were conducted using CLT Engineer software of Estora Enso Company. Connection design calculation was not included in design process. The take away of this project were being introduced to Eurocode regulation for designing of CLT buildings, and to CLT panel and connection producers ‘companies in Europe.

Final results of this project will be used for a comparison between the design of CLT buildings according to Eurocode 5 and the National Design Standard of

United States and adopting the European CLT design methods to expand the CLT building design in US.

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