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Fire Resistance of Large-Scale Cross-Laminated Timber Panels

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Abstract. Wooden structures are increasingly being used in the construction of residential buildings. A common and often published reason to avoid wooden structures is their insufficient fire resistance, which reduces bearing capacity. For this reason, composite sandwich structures began to be designed to eliminate this drawback, as well as others. Recently, however, the trend is for a return to the original, wood-only variant and a search is underway for new technical means of improving the properties of such structures. Many timber structure technologies are known, but structures made from cross-laminated timber (CLT) panels have been used very often in recent years. CLT panels, also known as X-LAM, are currently gaining popularity in Europe. In the case of CLT panels composed of several layers of boards, they can be said to offer a certain advantage in that after the surface layer of a board has burnt and the subsurface layer has dried, oxygen is not drawn to the unburned wood for further combustion and thus the burning process ceases. CLT panels do not need to be specially modified or coated with fire resistant materials, although they are usually lined with gypsum-fibre fire resistant boards due to guidelines set out in the relevant standards. This paper presents a new method for the assessment of load-bearing perimeter walls fabricated from CLT panels without the use of an inner fire-retardant lining to ensure fire resistance at the level required by European standards (i.e. those harmonized for the Czech construction industry). The calculations were verified through laboratory tests which show that better parameters can be achieved during the classification of structures from the fire resistance point of view. The aim of the article is to utilize the results of assessment and testing by an accredited laboratory in order to demonstrate the possibilities of using CLT panels for the construction of multi-storey as well as multi-purpose buildings in the Czech Republic.

1. Introduction

It has recently become a trend to construct buildings either wholly or mainly from wood. This is a way of building that has been neglected for many years in the Czech Republic, but the construction of wooden frame structures, panels, log cabins and timber houses is becoming more and more popular mainly thanks to the speed of construction, the price of the product, its emphasis on ecology and the aesthetics of wood. Modern wooden buildings are usually designed to be visually indistinguishable from brick buildings. The wood is hidden to the maximum possible degree under various layers of tiling and plaster. Moreover, the use of timber in construction is restricted to undemanding, relatively small, mainly single storey buildings and simple structures such as family homes and cottages. Why is this? Of course, lobbying carried out by the producers of masonry materials carries a partial share of

the blame, as well as the mistrust felt by people (and sometimes also the authorities) towards wood thanks to deeply rooted conventions, but the main culprit is the Czech legislation connected with building fire safety, which was not prepared for the current developments in this area and is thus evolving slowly and with difficulty.

Several research papers, professional papers and case studies dedicated to CLT fire resistance have been published in Europe and North America. Study [1] shows that the fire behaviour of cross-laminated solid timber panels depends on the behaviour of single layers. In another paper [2], the authors developed their own numerical model to predict the fire resistance of CLT floors and verified it via medium-scale tests. Large-scale tests were performed by the authors of [3] to demonstrate the behaviour of CLT floor panels with insulated wood board cladding when exposed to fire. Small-scale specimens were tested and presented in paper [4], which concerned the use of gypsum plasterboard as fire protection.

Currently, the Czech and Slovak Republics are the only countries which use the DP1 to DP3 classification of structures and elements according to the type of structural component they are for the purpose of determining their fire resistance. It is exactly this classification that is the main obstacle to the use of timber in building construction, particularly due to the fact that Czech standards almost prohibit the building of load-bearing structures or fire structures and elements from flammable materials. Despite the fact that our legislation is gradually being adapted in order to conform to European standards, the classification of structural parts is still required and its removal from the standards is not expected.

The aim of the research is to show that it is possible to build large, multipurpose and multi-storey buildings from timber - something which is already completely common abroad - even in the Czech Republic. And, that this can be done without hiding the wood inside non-flammable materials.

2. Materials and methods

2.1. Classification of the fire resistance of a wall

2.1.1. An overview of possible options. The classification of the fire resistance of an evaluated structure can be determined using:
- ČSN 73 0821 ed.2 – table value
- ČSN EN 13501-2 or 13501-3, where it is determined via classification based on test results
- Eurocode 1 and Eurocode 5
- calculation, but only in the cases where all agents influencing the resistance can be formulated numerically
- tests and calculation in cases when all agents cannot be included in the test, or when the test results require further evaluation

2.1.2. Other possible options, under special conditions:
- The publication "Values of fire resistance of constructions according to Eurocodes" – a table value which, however, only contains the fire parameters of wooden cross sections with a square or rectangular profile, not CLT panels
- The opinion of an expert witness from the field of building fire safety
- Certified testing of the structure to determine the fire resistance of its individual parts

However, these options do not always have to be acceptable to the authorities concerned –e.g. the Fire Brigade.

2.2. Input parameters of the calculation

2.2.1. Properties of wood. The main and indeed only material used in the load-bearing part of the wall is timber; this chapter lists the properties related to the fire resistance of wooden elements. The parameters are influenced by the type of wood and its moisture content. The listed characteristics correspond to the properties of spruce wood and the usual moisture content of structural lumber. The values are taken from ČSN 73 0822 [5] and ČSN 73 0824 [6].

The specific heat capacity of wood, c, is 1.55 to 2.28 kJ/kgK. The coefficient of thermal conductivity for the direction parallel to the fibre and 12% moisture content is 0.12 to 0.18 W/mK. For the direction perpendicular to the fibre and 12% moisture content it is 0.25 to 0.45 W/mK.

The calorific value of wood, H, depends on its moisture content as all the water contained in timber evaporates during burning. For this transformation of water (liquid) into vapor, part of the energy which was created by the burning of the dry matter is consumed. The calorific value of dry matter ranges from 17.5 to 22 MJ/kg for all types of wood. In the case of a standard moisture content (w=25%) this calorific value drops to about 15 MJ/kg [7]. For a moisture content of 15% the calorific value equals approximately 17.9 MJ/kg, and for 12% it is around 13.4 MJ/kg. According to the standard [6], the H value for the calorific value of coniferous wood with a moisture content of 15% equals 17 MJ/kg with the coefficients K =1.0 and k_{p1} = 0.7.

The ignition temperature, i.e. the lowest temperature to which wood must be heated in order for it to self-ignite, is 330 to 470°C. However, the flash point (the lowest temperature at which so much gas develops in the wood that it creates a mixture with the air which ignites when it gets close to a flame) is only 180 to 275°C, the burning point then being between 260 and 290°C,[7].

The time to ignition of wood in relation to temperature is 19.6 sec for 200°C, 5.3 sec for 250°C, 2.1 sec for 300°C, 1.0 sec for 350°C and 0.3 sec for 400°C.

The flame spread index for unmodified planed spruce is i_s=54, while for boards made from layered wood it is i_s=57. In the standard [5] it states that boards made from layered wood should be no more than 15 mm thick. The flame spread index can be lowered to 30 with the fireproof coating suggested in the relevant standard.

The standard temperature for a fire after overall ignition has occurred was calculated according to the following relation (1):

$$T_n = T_0 + 345 \, \log_{10}(8t + 1) \tag{1}$$

The heat transfer in one direction was calculated according to the relation (2):

$$\frac{dT}{dt} = \frac{ad^2T}{dx^2} \tag{2}$$

The thermal conduction coefficient was calculated according to the formula (3):

$$a = \frac{\lambda}{c\rho} \tag{3}$$

where T is the temperature increase, dt is the time increase, dx is the thickness of the layer in the direction of axis x, *a* is the coefficient of thermal conductivity, $T_0 = \Theta g$ is the standard temperature curve, T_0 is the initial temperature (20°C for the investigated case), t is time, α is the coefficient of heat transfer through flow (25 W/m^{2}K for the investigated case), ρ is the specific weight, λ is the coefficient of thermal conductivity, and c is the specific heat.

2.2.2. Input data for statistical evaluation. The statistical evaluation of the reference model of the structure was calculated using the input data stated in Table 1 and Table 2.

Table 1. Input data for statistical evaluation

Input data	Value
Number of storeys	max 4 (for fire height h = max 12 m)
Storey height	max 3 m
Ceiling span	max 6 m
Snow area	4
Wind divergence	4 (30 m/s)
Service class	1
Wall thickness	84 mm (without lining)

Table 2. Expected maximum load

Input data	Value
Characteristic imposed load	2 kN/m^2 (category A according to ČSN EN 1991-1-1)
Characteristic weight of roof	1.41 kN/m^2 (flat roof with gravel)
Characteristic weight of ceilings	2.41 kN/m^2 (heavy ceiling)
Characteristic weight of walls	2.41 kN/m^2
Total vertical load	G_d = 109.2 kN/m'

3. Results and discussions

The experiment concerned the evaluation of a load-bearing peripheral wall composed of 84 and 124 mm thick CLT panels, some with and some without fire protection in the form of an inner lining made from gypsum fiber board that extends the period of fire resistance of the CLT panel for structural components of the DP3 type, as well as (and mainly) for components of the DP2 type.
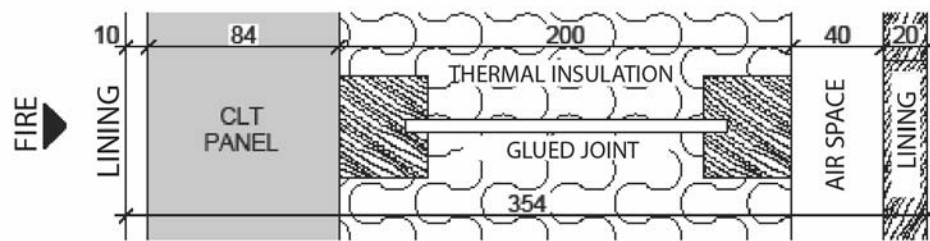
3.1. Composition of the evaluated structure

3.1.1. Load-bearing part of the structure. The structure is a large-scale multi-layer panel of the CLT type where each layer of the panel is composed of lamellas made from solid spruce wood. The orientation of each individual layer is always perpendicular to the neighbouring layers. The lamellas in each layer are glued in the longitudinal and transverse directions and the layers are glued to each other.

3.1.2. Inner lining of the load-bearing structure. With regard to the requirements concerning fire safety measures, the individual panels are either protected with a fire screen on the inner side which works together structurally with the load-bearing part of the wall, or alternatively are left without surface treatment. Usually, gypsum fibre board or plasterboard panels are glued directly onto the wooden panel. Other types of fire protection, for example coatings or sprays, or heat shield claddings, etc. have not been evaluated in a laboratory or numerically yet. The option of using coatings is described in its own individual chapter, while the evaluation of heat shield claddings has yet to be considered.

3.1.3. Outer lining of the load-bearing structure. On the outside, the panels are supplemented by a ventilated façade of a thickness that corresponds to current legislative requirements for passive houses concerning the thermal energy performance of buildings.

The ventilated façade was chosen with the aim of using maximal natural materials, mainly wood, and it will be evaluated in a different stage of the research. The fire load of the structure is, for the time being, evaluated only from the inner (interior) side: the outer lining of the structure does not have an effect on the results of calculations and tests at this stage. The composition of the structure is visible in Figure 1.

Figure 1. Vertical section through the evaluated structure (the composition corresponds to sample No. 2)

3.2. Thermal technical parameters of materials included in the calculations
The initial average temperature of the surface of the sample is 17.3 °C. The results of the calculation of standard temperature are presented in Table 3.

Table 3. Calculation of standard temperature.

	Numerical equation notation	Standard temperature
0 min.	$20 + 345 \log_{10} 1$	20.00
5 min.	$20 + 345 \log_{10} 41$	576.41
10 min.	$20 + 345 \log_{10} 81$	678.43
15 min.	$20 + 345 \log_{10} 121$	738.56
20 min.	$20 + 345 \log_{10} 161$	784.35
25 min.	$20 + 345 \log_{10} 201$	814.60
30 min.	$20 + 345 \log_{10} 241$	841.80

The thermal conductivity coefficient was calculated (4):

$$a = \frac{\lambda}{c\rho} = \frac{0.32}{1150 \; 1100} = 2.52967\mathrm{E}^{-07} \tag{4}$$

The heat absorption capacity of the whole boundary structure is defined using the relation (5):

$$b = \rho c \lambda \tag{5}$$

The value of heat transfer in one direction was calculated as (6):

$$\frac{718.56}{900} = \frac{2.52967 \, \mathrm{E}^{-07} \; 718.56^2}{0.01^2} \tag{6}$$

3.3. Structural assessment of the reference model
A structural assessment was performed on an 84 mm thick CLT panel without lining for the purpose of comparison with the test result. A simplified model of the structure was created as the basis for the calculation which was designed in such a way that it covers the majority of buildings this evaluation focuses on – i.e. mainly residential buildings. The calculation was carried out according to Eurocode 5 [8].

3.4. Assessment of fire load
The wall was evaluated as regards for R45 minutes, i.e. a 15 minute longer fire resistance was selected than that classified on the basis of the test, i.e. R30, where the load-bearing capacity was maintained in reality for a period of 35 minutes. The results are shown in Table 4.

Table 4. Results of the fire load assessment

	Value
Original wall thickness	84.00 mm
Burnt part of the wall	36.25 mm
Undamaged part of the wall	47.75 mm
Ultimate limit state	0.60 ≤ 1 (reduced cross section method)

The wall meets the requirements for fire load with the result 0.46 ≤ 1 (reduced properties method). The fire resistance of the wall is at least R 45.

4. Conclusions

The following conclusions can be stated for the REIW assessment:

- The integrity of the structure was preserved for the whole period of the test, i.e. 60 minutes.
- The 20 kN/m load bearing capacity required for an exerted load was fulfilled for the whole period of the test, i.e. 60 minutes
- After a period of 60 minutes, the damage to the insulation panel had only progressed to halfway through the panel, which meets the conditions for an average temperature growth of 140 K, or a maximum temperature of 180K. The panel would meet the insulation assessment conditions even if its thickness was only 42 mm.
- In the case of heat radiation, it can be expected that the structure should meet this criterion when the remaining effective thickness is over 30 mm. At the same time, the requirement for insulation is also fulfilled and thus amount of radiation will also meet the requirements for 60 minutes.

When evaluating the experiment as a DP2 type of structure, the following conclusions can be drawn:

- If the average temperature of the point of ignition is 275°C, a class C1 wooden board will ignite after 16 minutes at the earliest, and after 17.2 minutes on average.
- The evaluated structure can be classified as a DP2 type of structure for 15 minutes, after which it is immediately ranked as a DP3 type of structure.

In order to be able to achieve better parameters for the classification of the structure as the DP2 type, e.g. REI 30 DP2 or REI 45 DP2, it needs to be ensured that the wooden structure does not ignite for a period of at least 30 or 45 minutes, respectively. The following measures can be taken:

- Increase the thickness of the fire resistant boards or use two boards.
- Change the type of evaluated lining for a board with higher fire resistance.
- Replace fire resistant boards with heat shield cladding.
- Supplement the evaluated structure with further fire protection – coatings, plaster, etc. It is evident that the behaviour of a layered panel is different from that of solid wood, which according to the relevant ČSN standard is in class D with regard to its reaction to fire. With protective coatings, it is definitely possible to achieve class B for reaction to fire.

It is also possible to try to move a component to a better class for reaction to fire. It is necessary to check via laboratory testing whether the average temperature of the point of ignition is really only 275°C for a specific type of wooden panel. It should be mentioned that any improvement in test results will only be a cosmetic one, within the order of 2-3 minutes.

During the course of the 60 minutes when the test was executed, the calculated standard temperature was approximately the same as the average temperature in the testing room. It is the case

that the wooden structure was damaged, but the increase in the intensity of the fire in the burning area is demonstrably negligible.

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