Fire resilience as a sustainability characteristic
Are residential CLT buildings fire resilient?

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Introduction

Cross Laminated Timber (CLT) is gaining popularity because wood is a sustainable building material. In addition, unprotected wooden structures and separation constructions can be sufficiently fire-resistant according to the standard fire curve when the burning depth in the wood during the time that the construction must be fire-resistant is taken into account. The assessment criterion is that after that time the reduced cross-section still offers sufficient strength and thermal resistance in case of fire.

But is the structure also able to survive a fire? Is the construction not only fire resistant but also fire resilient? This would mean that the building could be restored after a fire with limited repairs. The fire has to be remain within the compartment. A multi-compartment fire is not acceptable. In addition, it is questionable whether replacement of structures can still be regarded as fire resilient.

Figure 1. CLT house under construction

Fire resilience and the public law assessment framework

The public law assessment framework in the Netherlands is currently laid down in the Building Code (Bouwbesluit 2012). As in most other countries, it concerns a collection of prescriptive regulations, which can roughly be classified into the following derived objectives (or risk subsystems):

1. Safety of building users (escape route)
2. Safety of emergency services (attack route)
3. Safety of compartments and sub-compartments (preventing fire and smoke spread in the building)
4. Safety of the building (fire resistance of load bearing structure)
5. Safety of the environment (preventing fire spread to neighboring plots)

The main objectives under public law that must be safeguarded in this way are the personal safety of building users and emergency services and the safety of property belonging to third parties (neighbouring plots). The above derived objectives 1, 2 and 5 are directly related to the main objectives. The derived objectives 3 and 4 can be seen as Lines of Defence (LODs), with which time can be gained, so that the main objectives can be achieved more easily.

When the aforementioned LODs (derived objectives 3 and 4) are performed with a high reliability, a building can be prevented from burning down. If the fire remains limited with a large amount of certainty to a limited area, the building can be called fire resilient. This is possible with an active extinguishing system, but also with reliable fire compartmentation. Reliable fire compartmentation means that the fire resistance is larger than prescribed in the Building Code and the connection details prevent flanking fire spread (such as by the façade).

Is that possible with wooden buildings? Or more specifically: Is that possible with buildings in CLT?

Load bearing timber structure

An unprotected load bearing timber structure can be sufficiently fire-resistant when the burning depth leaves a sufficient cross-section to be able to transfer the mechanical forces. The Eurocode provides a calculation method for this that takes into account the duration over which the construction must be fire-resistant.

The implicit point of departure is that the construction does not continue to burn after that period of time has elapsed. In other words: the fire in the construction extinguishes simultaneously with the fire in the compartment. That's not so logical. It is conceivable that the structure will continue to burn and eventually collapse.

In the case of laminated constructions, the burning depth can also be accelerated because the glue softens or starts burning along and the lamels come loose from the construction.

Conversely, it is also conceivable that the burning rate slows down because the char layer that is formed on the surface has an insulating effect, as long as the char layer does not fall off the construction.

However, in all cases the load bearing structure that survives the fire is no longer usable after the fire. The reduced cross-section will be insufficient for the normal mechanical use load. In practice, replacing the structure will be the only option. A fire-resistant load bearing timber structure is therefore not fire resilient without protection (Zee, 2018).

Figure 2. In residential buildings, the load bearing structures are also separation constructions

Compartmentation by timber separation constructions

For separation constructions of fire compartments the thermal resistance plays an important role. The thermal resistance needs to ensure that the EI or EW criteria (fire resistance in minutes standard fire curve) according to NEN-EN 13501-2 are met.

However, meeting the criteria according to NEN-EN 13501-2 says nothing about the failure probability of the separation construction. The failure probability is determined by the thermal load as a result of the fire and the thermal resistance (fire resistance) of the separation construction. In fact, this is an RST-AST analysis. The RST (Required Safe Time) is the thermal load provided by a fire, expressed in minutes standard fire curve. The AST (Available Safe Time) is the fire resistance of the separation construction, also expressed in minutes standard fire curve.

As long as AST > RST, the separation construction is successful, the construction being more reliable the larger the AST-RST interval.

The standard fire curve is used to determine the fire resistance using of standardized test methods. However, the actual temperature development of a fire in a fire compartment does not follow the standard fire curve, but is determined by project-specific building and fire characteristics. In a natural fire concept according to the Dutch standard NEN 6055 it is possible to value these characteristics.

For example, for a small compartment with a residential function (70 m^2 apartment), the difference in the thermal load (RST) between traditional concrete structure and modern timber structure in CLT has been considered. In both situations, the apartment has daylight openings in two façades that are not fire-resistant. This means that after flashover the glass in the daylight openings will fall out.

The daylight openings are assumed to have the dimensions that after flashover the fire is in the transition from fuel-controlled to ventilation-controlled. This leads to the largest thermal load and can therefore be seen as worst-case.

Figure 3 gives a simple representation of the fire compartment. Table 1 gives an overview of the most important boundary conditions, based on a cellulosic fire load with fuel formula $C_4H_6O_3$ (NEN 6065).

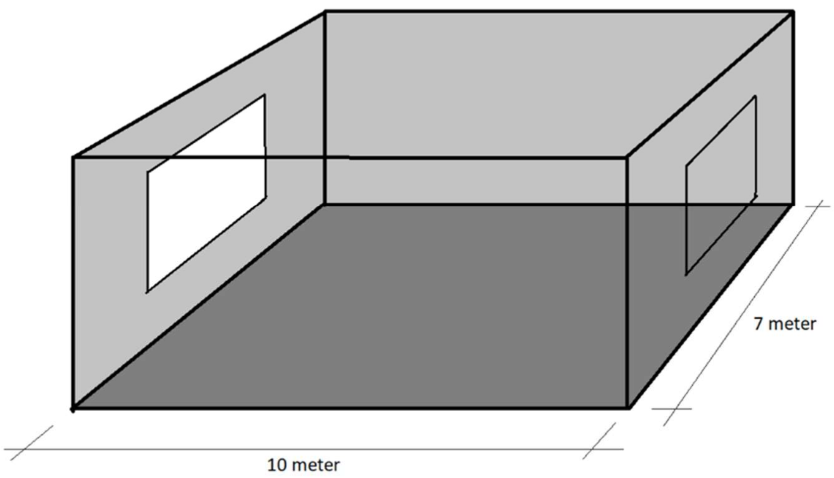

Figure 3. Isometry of the fire compartment (apartment)

Table 1. Overview of boundary conditions for the natural fire

Greatness		Traditional	CLT
Permanent fire load (average)	[MJ/m^2]	-	400 [(2)]
Variable fire load (average)	[MJ/m^2]	780 [(1)]	780 [(1)]
Fire power density	[kW/m^2]	250 [(1)]	250 [(1)]
Time constant fire development	[s]	300 [(1)]	300 [(1)]
Combustion value	[MJ/kg]	17,5 [(3)]	17,5 [(3)]
Stoichiometric constant	[kg/kg]	1,27 [(3)]	1,27 [(3)]
Combustion efficiency	[-]	0,8 [(3)]	0,8 [(3)]
Collapsed daylight openings h x b	[m]	1,5 x 8,2 (total)	1,5 x 8,4 (total)

(1) According to NEN-EN 1991-1-2/NB
(2) Assuming a characteristic permanent fire load of 500 MJ/m^2
(3) According to NEN 6055

The thermal load due to the gas temperatures as a result of a natural fire in the apartment is translated in both situations into an equivalent fire duration according to the standard fire curve. The equivalent fire duration follows from the accumulated internal gas energy of the total natural fire duration. The difference in thermal load due to fire in a traditional apartment with that in a modern CLT apartment is clearly visible in figure 4.

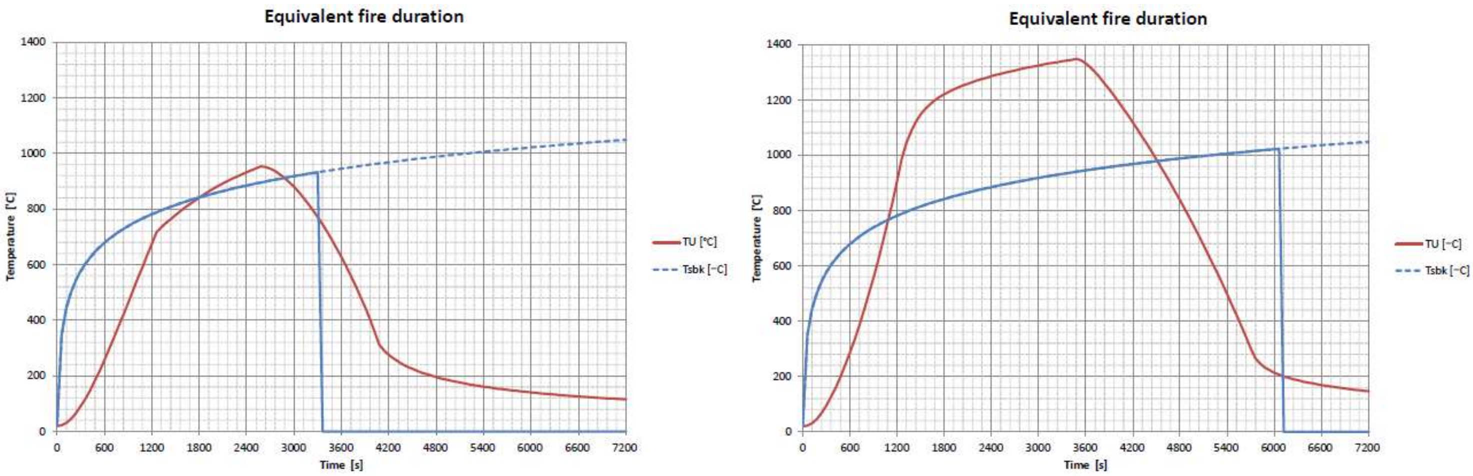

Figure 4. Natural fire curve and conversion to equivalent fire duration according to the standard fire curve for a traditional apartment (left) and a CLT apartment (right)

Figure 4 shows that the equivalent fire duration in a traditional apartment is approximately 54 minutes and in a CLT apartment 101 minutes. When the separation constructions of the fire compartment are 60 minutes fire resistant, there is a clear shortage of fire resistance for the CLT apartment:

- Traditional apartment: AST – RST = 60 - 54 = +6 min. standard fire curve;
- CLT apartment: AST – RST = 60 - 101 = -41 min. standard fire curve.

If no action is taken in the natural fire duration (automatic or manual suppression), the CLT building with residential functions will burn down. Although this is acceptable under public law as long as personal safety of the building occupants is guaranteed, the building is not fire resilient. The building cannot survive an apartment fire without suppression by the fire service.

Quantifying the risk of failure

The failure risk can be quantified by determining the failure probability of the normative effect. This is the probability that the thermal load is greater than the fire resistance of the structure. In formula form: P_{falen} = P (RST > AST).

The fire resistance (AST) has been determined deterministically using a fire resistance test according to the standard fire curve. The failure probability plays no role in this determination method.

The thermal load is determined project-specifically on the basis of the natural fire concept. In this context, boundary conditions with uncertainty (stochastics) play a major role in the reliability of the thermal load. The influence of the stochastic boundary conditions on the thermal load can be determined by means of a sensitivity analysis, in which each stochastic boundary condition is individually varied with its standard deviation.

The summation of the specific partial variances of the stochastic boundary conditions yields the variance (and thus the standard deviation) of the probability distribution P (AST < RST), see figure 5.

Each boundary condition (x_i):	
Average value:	$\overline{x}_i$
Variation:	dx_i
Standard Deviation:	s_i
Impact on outcome AST−RST (t):	
Variation:	dt
Specific Variation:	dt/dxi
Specific Variancy:	$(s_i\, dt/dxi)^2$
Probability AST−RST :	
Total Variancy:	$var = \sum_i (s_i\, dt/dxi)^2$
Standard Deviation:	$s = \sqrt{var}$

Figure 5. From standard deviation per stochastic boundary condition to specific variancy and finally to standard deviation for AST-RST.

The most important stochastic boundary conditions concern the fuel characteristics. The stochastic values included in the sensitivity analysis are shown in Table 2 (Benen et al, 2018). There is also one building characteristic included in the stochastic boundary conditions, the permanent fire load of the compartment. This is only important for the CLT compartment, because it is not known whether the entire CLT construction burns and what the pyrolysis rate is (Rinta-Paavola et al, 2021).

Table 2. Overview of stochastic boundary conditions with average value and estimated standard deviation

Stochastic	Average (AVG)	Standard deviation (SD)
Permanent fire load [MJ/m2]	0 (traditional) 400 (CLT)	0 (traditional) -300 [(1)] / +120 (CLT)
Variable fire load [MJ/m2]	780	-120 / +120 [(2)]
Burning power density [kW/m2]	250	-100 / +100 [(3)]
Time constant fire development [s]	300	-100 / +100 [(3)]

(1) Based on an extinguishing fire in the CLT structure when the variable fire load is burned
(2) Based on NEN-EN 1991-1-2/NB
(3) Based on rating bandwidth

The consequence for the thermal load RST in equivalent fire duration (SFC) has been determined for each variation. The standard deviation of the thermal load RST is determined from this. The variable fire load seems to be the significant stochastic. The results are summarized in Table 3 and shown in Figure 6.

Table 3. Average value and standard deviation of the thermal load due to fire for a traditional apartment and a CLT apartment

	Traditional [min. SFC]	CLT [min. SFC]
Average thermal load	55	101
Standard deviation thermal load	-13,4 / +13,4	-26,6 / +14,0

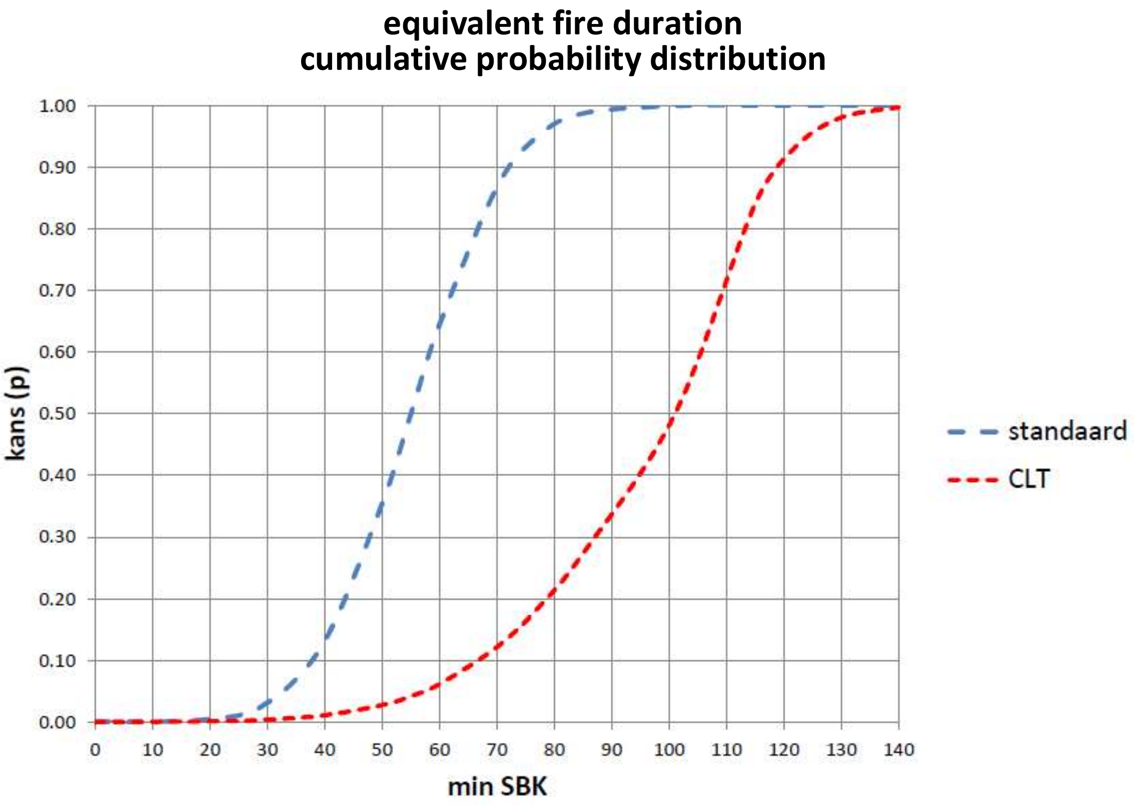

Figure 6. Cumulative probability distribution (p) of the thermal load due to fire in minutes standard fire curve for a traditional apartment and a CLT apartment

Conclusion

The analysis shows that a 60-minute fire-resistant separation construction in a traditional apartment is approximately 64% reliable, which means that it has a probability of failure for the natural fire of approximately 36%. The failure probability of a 60-minute fire-resistant separation construction in a CLT apartment is 93%. This means that in the event of a fire in a CLT residential building, a burn-down scenario is almost certain if no action is taken in the fire scenario by automatic or manual extinguishing. A CLT residential building is therefore not fire resilient. To achieve this, protection of the CLT construction is necessary.

This protection can be a fire-resistant lining, coating or cladding, or an installation-technical protection that intervenes in the fire scenario (automatic fire extinguishing installation). More innovative solutions can also be envisaged, such as a protective coating that keeps the char layer on the surface intact during the fire, stopping the burn-in speed over time (Schmidt, 2020).

Incidentally, there is a chance that the fire in the CLT construction will extinguish when all variable fire load has been burned. Then the CLT construction is partly preserved (Crielaard, 2015). The remaining part of the construction that has been exposed to the fire will no longer be suitable for meeting normal usage requirements. This needs to be replaced, but has ensured that the fire has been limited to one compartment. As a result, the CLT constructions outside the burned-out compartment are not affected.

In other words: if a CLT construction has such a quality that it cannot burn independently and therefore extinguishes when the variable fire load in a fire compartment has been burned, fire resilience comes within reach.

This condition does not have to be met in case of land-bound homes if the CLT construction of a home is independent of the adjacent home. By using mechanically and thermally separated CLT constructions at the location of the residential separation, one can also speak of fire resilience. The fire can then no longer automatically spread to the adjacent compartments. The detailing, especially the connection to the facades, deserves special attention.

Literature

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