# PERFORMANCE-BASED DESIGN OF FIRE SAFETY IN HIGH RISE CLT BUILDINGS

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## INTRODUCTION

The construction industry throughout the world is pushing the development of more buildings constructed completely in timber to a much greater extent than before. The properties of timber, especially Cross Laminated Timber (CLT), bring many new benefits, but fire safety remains a challenge.

This abstract focuses on the fire safety issues arising from constructing high rise buildings with CLT volume elements. Six problem areas have been identified and will be addressed. For the purpose of this abstract a high-rise building is considered to be sixteen storeys or more.

The construction of a CLT building is challenging in many ways. More intense fire scenarios can occur if timber finishes are exposed. This has an impact on the capacity of the loadbearing structures, increases the risk for fire spread via openings and also the occupant safety within the fire compartment or adjoining egress paths to the fire compartment. Some of these issues have been addressed in [1] but many challenges still remain.

Another challenge for CLT buildings with a rise in storeys of six above the ground is that the structure and passive fire separations must be designed to withstand vibrations in the structure due to the moving loads inside the building and wind loads. The vibrations are a problem for buildings over eight storeys and for buildings over sixteen storeys, this is a significant problem.

Due to the complexity of high rise CLT buildings and the limited experience that exists within the industry, the fire safety design is time-consuming. The construction time of a CLT building is however, shorter than that of other types of building structures, as is the case for timber buildings in generally.

As a timber structure, may shrink over time, especially during the first year, the connections between CLT elements can be compromised and need special attention.

There is still no adopted product standard to achieve conformity of CLT products. This could potentially be a part of the European standard in 2018.

## PROBLEM AREAS

Using timber as a building material is nothing new and has been done throughout history. Nonetheless, there are significant challenges to demonstrate an acceptable level of fire safety for high rise CLT buildings. To address these this abstract focuses on the following different problem areas:

1. Combustibility of timber;
2. Risk of fire spread via cavities between CLT elements;
3. Robustness to the fire safety design;
4. Damage caused by a fire;
5. Detailing in high rise CLT buildings; and
6. Fire safety and fire protection during construction.

### 1. Combustibility of timber

Wood is combustible and this combustibility will add fuel load to a fire. To represent a compartment fire standard fire tests are widely used. To describe a real fire scenario i.e. fully developed flashover fire including the decay phase, the parametric fire curves based on correlations can be used [2]. The standard fire test used to determine a fire resistance level of building elements follows a pre-determined temperature curve (e.g. ISO 834 or ASTM E119). If an unprotected CLT wall or CLT ceiling is tested using a standard fire test, the unprotected timber surfaces will ignite and increase the temperature inside the compartment. This results in less fuel being used by the test furnace heaters to keep the pre-determined temperature curve. The fire may be *ventilation controlled* which will have a minor influence on the fire exposure tested.

The standardization of a real fire scenario, for example by using the parametric fire curve is based on many assumptions. In a compartment with combustible linings exposed, its adequacy to represent the conditions in a real fire scenario may be compromised. The increased fuel load will contribute to longer lasting fires and increased intensity of the fire in its early stage. The larger extent of unburnt fuel ventilating out from the fire compartment will increase the risk of fire spread via openings.

The most common approach to protect the CLT is using fire rated plasterboard to achieve a fire resistance rating as determined in a standard fire temperature curve test. The standard approach used internationally to determine how much plasterboard protection is required relates to the critical temperature of 300 ˚C, which is deemed to be the temperature when timber starts to char [3, 4]. It is important to understand that heat will transfer through the plasterboard layer(s) into the CLT element and pre-heat the structure before charring occurs. This therefore increases the risk that layers of CLT will delaminate before the plasterboard has lost its complete fire resistant capacity. Over time the plasterboard will lose its fire resistance capacity and will eventually fall off, especially true of plasterboard in ceilings. Once the plasterboard layer has fallen off, the pre-heated CLT elements will be exposed and consequently a second flashover in the fire compartment may occur.

The charring will reduce the loadbearing strength of the CLT structure and there are approaches to determine the expected fire resistance in a timber structure using charring calculations over time. These methods are adopted from fire tests of different timber materials and presented in several design methods such as the Eurocode 5 [4]. The main problem with using these charring calculations for CLT elements is that the layers of CLT delaminate which subsequently impacts on the charring rate making them inaccurate [5, 6], New methods have been developed [7] and are proposed to be included in the revised Eurocode 5, ‘Design for Timber Structures’, potentially to be published in 2022.

Full-scale real fire scenario testing for CLT construction is presently limited and the fire performance of CLT has in many instances been assumed to perform as massive timber. The expected fire resistance can be demonstrated based on standard fire testing or performance based design, the accuracy must however be considered.

The delamination has been demonstrated in full-scale real fire scenario tests and results show that specimen shape and the number of layers affect the resistance to delamination. The temperature rise in CLT will affect the glue in such a way that the layers may delaminate. At this point, unburnt timber will be exposed to the fire. This is the reason why full-scale real fire scenario tests have witnessed a second flashover in the fire compartment. Some CLT uses thermoplastic polyurethane adhesive with a melting point of 210 °C [8]. It should be noted that the cohesive failure of the adhesive glue will occur at temperatures below the melting point [6].

Heat-resistant adhesive can be used to mitigate the risk of delamination. The length of screws used to fix any protective layers of plasterboard should be used to strengthen the connection between the first layers of CLT to the second layer.

The standard time-temperature exposure fire tests do not consider the decay phases in a real fire scenario. Therefore, the effect of delamination is not accounted for [9].

Different critical heat fluxes inside the fire compartment are commonly used to determine self-extinction of exposed CLT surfaces. However, as there are currently no theoretical methods to quantify the expected delamination of CLT in a real fire scenario, self-extinction of CLT construction cannot be estimated without disregarding delamination. If relying on self-extinction and designing for burnout the CLT must, therefore, be protected to a degree that it remains intact during the real fire scenario [10].

If exposed timber is used in the building, a parametric fire curve must be adjusted to take this additional fire load into account, together with the possible risk of delamination. This could be adjusted as per the provisions and general recommendation on the application on European design standards used in Sweden today, which recommend a safety factor of 1.5 times the fire load [11]. Some adjustments may also be needed to address the possibility of a faster temperature rise and a longer fire scenario with additional flashovers occurring due to the delamination.

### 2. Risk of fire spread via cavities between CLT elements

The CLT volume element connections may create small cavities. These cavities can pose a potential risk for fire spread horizontally and vertically in the elements. Different types of fire stop or insulation materials can be used to fill these cavities, but it must be done before any encapsulation of the CLT.

Cavities may be needed to assure good acoustic performance of the building, but it is important that these are sealed not to compromise the fire safety and sealants must be checked.

Movements in the timber structure will impact the connections between the CLT elements and the sealant must be adapted to suit this. This applies for connection between CLT and protective plasterboard. Penetrations into the CLT structure may also impact the risk of fire spread via these cavities if located unfavourably and not protected adequately.

### 3. Robustness to the fire safety design

As described above, the design of a timber building is complicated and the fire safety design today is based on many uncertainties. Robustness in the fire safety design is therefore of great importance.

To limit the maximum fire damage area (volume) a risk analysis is necessary to address robustness in the design. The following technical fire protection systems should be included one by one as part of the analysis:

- Automatic fire and evacuation alarms;
- Automatic fire suppression systems;
- Automatic smoke ventilation or any other system limiting the spread of fire and smoke; and
- Lifts used for evacuation.

The more critical fire protection systems should then be analyzed to identify weaknesses or dependencies in these systems that need additional robustness [12]. Consequential failures should be considered if the event can disable multiple systems, e.g. power failures or signal errors. One of the several methodologies for risk analyses that can be used are presented in [13, 14].

The passive fire protection within a fire compartment should also be addressed as a fire protection system as per above. A maximum area of acceptable damage due to the collapse of separating structures, both horizontally and vertically, must be addressed. Some designs of high rise buildings today have used the approach of dividing the building into horizontal sections with additional fire barriers between them. This to allow for longer evacuation times, make fire brigade intervention easier and create additional redundancy in the design against the risk of fire spread.

The provisions and general recommendation on the application on European design standards used in Sweden today, require that buildings higher than eight floors to have a safety factor 1.5 times the fire load [11]. The provision of an automatic fire suppression system allows the design fire load to be reduced with a factor of 0.6 [11]. This might be one way of solving the robustness for loadbearing structures and the applicability for CLT construction can be evaluated further.

## 4. Damage caused by a fire

There are two types of major problems after a fire in a timber building, the residual strength in the timber construction itself and water damage.

Either the wood construction is completely destroyed and must be replaced or there are uncharred portions of the wood that remain intact. In the latter new outer parts of protective boards can be assembled after the charred wood has been removed and it has been determined that there is sufficient uncharred timber that will maintain its loadbearing capacity.

It must be determined that the layers of lamination in the CLT have not been damaged or the adhesive has lost its strength. For longer lasting fires the heat transfer into the structure may have damaged the structure without being visible.

Water damage may also be an issue for timber buildings. The possibility for the fire brigade to shut off an automatic sprinkler system should be explored in the design process to provide means to minimize the potential water damage. The use of automatic mist sprinkler systems, requiring less water, could also be a possible replacement to the conventional sprinkler system.

For CLT buildings the fire brigade intervention may have more importance in the later stages of a fire due to the structure being combustible. To improve the efficiency of a fire brigade intervention in a CLT building a response plan must be designed together with the local fire brigade. Allowing a better understanding of the building and the potential fire scenarios that can be expected. This could potentially also mitigate the unnecessary extent of water damage caused by the fire brigade which could be more severe than from an automatic sprinkler system.

The possibility of joining the building horizontally in “water tight” zones at every third level should be explored to minimise a worst-case water damage scenario to be limited to three floors.

A plan of action after a fire to minimize the water damage should also be set up by stakeholders.

## 5. Detailing in high rise CLT buildings

Installation of insulation products together with the fixings used for potential protective claddings is critical and must be done correctly. Any cavities in the structure and penetrations must be accurately sealed with fire stops and the work must be checked and monitored during the construction phase [9].

Quality assurance is essential at many levels, especially inspection of on-site construction. Self-monitoring by the contractor is in many cases not sufficient enough for tall solid wooden buildings due to the experience of self-monitoring of building works and the adequate education and training of the working force [15].

Therefore, third-party control and rigorous quality management systems are needed and their use on site is essential to be used on the site the during the erection time.

## 6. Fire safety and fire protection during construction.

During construction of timber buildings, the timber surfaces may be exposed and the final fire safety measures required for the building may not yet be in place.

One of the most important aspects of fire safety design is compartmentation, which is not completed until the end of the construction. The main importance of the compartmentation is to limit the size of a fire in the building, which has a direct impact on the safety of evacuating occupants, the risk of fire spread between levels and neighbouring building and fire brigade intervention.

The risk of fire ignition on a construction site is also increased when the entire structure of the building contains combustible building materials. Welding, hot works, power tools and smoking are some ignition sources on a construction site that must be considered. As a construction site is constantly changing risk assessments for the potential fire risk must also be continuously evaluated.

Arson during non-working hours should be taken into extra consideration due to a number of combustible materials. Surveillance or other measures must be taken. The workforce should be more aware of the potential of fire risk through educational efforts and training [16, 17].

## CONCLUSIONS

Due to the complexity of high rise CLT building and the limited experience within the industry, the fire safety design will be time-consuming and need to be addressed carefully.

Unprotected CLT will create more intensive fires and increase the risk for fire spread via openings and also occupant safety within the fire compartment or adjoining egress paths to the fire compartment.

A second flashover, due to protective boards falling off and/or delamination, must be addressed in the fire safety design. It is important to understand that heat transfer through the protective layer(s) into the CLT wall and pre-heat the structure.

Connections between CLT volume elements will create small cavities that pose a potential risk for fire spread horizontally and vertically. These must be sealed accordingly to protect against the spread of fire between the elements.

The design of a CLT building is complicated and the fire safety design today is based on many uncertainties. Robustness in the fire safety design is therefore of great importance.

The loadbearing structure in a timber building should be designed to withstand a real fire scenario, including the decaying face of the fire. Instead of relying on a standard fire test, demonstrating that a system will withstand exposure to the standard fire curve.

The residual strength in the CLT construction and the potential water damage are the main consequences that must be addressed after a fire.

CLT is a new and complex building material, self-monitoring by the contractors is probably not sufficient enough for tall solid timber buildings. Therefore, a third-party control and a rigorous quality management system are essential during the erection process.

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