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FIRE SAFETY ENGINEERING OF BUILDINGS WITH VISIBLE TIMBER CONSTRUCTIONS

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ABSTRACT:

Is it possible to build high rise timber buildings without sacrificing fire safety?

On a global basis, the use of timber as building material is rapidly increasing. Fire safety engineers meet new challenges compared to prevalent design with incombustible building materials. There are several questions and problems which must be addressed for the engineer to design a firesafe building from wooden construction materials.

The ambition of the project Mjøstårnet was to build the tallest wooden building in the world, at the same time being a distinct wooden building allowing visible wooden constructions. These ambitions may come into conflict with Norwegian fire regulations that requires the building to withstand a complete burnout without structural failure of the primary load bearing system. Standard fire safety calculations will not verify neither burnout nor required fire resistance to withstand burnout with combustible construction materials. A common belief, also reflected in the building regulations, is that surviving burnout requires incombustible materials, or incapsulating combustible construction materials, hence disfavoring the choice of timber as a building material. To address these challenges, an innovative approach was established for the design and verification of legal requirements for the tallest wooden building in the world, Mjøstårnet.

KEYWORDS: Fire safety, massive timber, highrise buildings, Mjøstårnet

1 INTRODUCTION

1.1 SUSTAINABLE QUALITIES

Wood is one of the most sustainable and environmentally favorable construction materials available. This is due to its absorption of carbon dioxide while growing. Wood is a renewable material, it lasts a long time, can be recycled and reused, it's great at retaining heat, its waste is 100 percent biodegradable, and it has a positive effect on your physical and mental health[1,2,3].
Pressing environmental concerns and urgent housing needs, urban densification, and the use of existing resources together with otherwise sustainable materials are of key importance for the increasing use of timber.
Besides its many other benefits, timber as a construction material is especially suitable due to its low weight and ample prefabrication possibilities.

1.2 FIRE SAFETY

Working with fire safety in wooden buildings, the fire safety engineers meet new challenges compared to traditional design with incombustible building materials. There are several questions and problems which must be addressed for the engineer to design a firesafe building from wooden construction materials.

- Firstly, can the loadbearing system resist fire when the construction materials themselves burn?
- Secondly, can existing calculation methods and test criteria, often based on incombustible materials, be utilized in the design?

There is an ever-growing base of experimental evidence and related guidance documents that shed light on these questions. Just in the last few years there are a number of review papers that summarizes the experimental work done on fire in timber compartments [4,5,6,7]. These highlight some of the gained knowledge and future challenges. A recent paper [6] reviews 63 compartment fire experiments involving timber constructions, the majority of which use cross laminated timber (CLT). The recent experiments show that timber constructions can survive a full duration [8,9] of a fire deemed "burnout", however the papers also address some challenges. Some of these include significant uncertainty and variability in for instance charring rates. They also highlight the need for more research on a range of compartment configurations, including larger compartment sizes.

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Although the major focus on recent research effort is CLT elements, it highlights an important difference between CLT and common constructions elements like glue-laminated members (Glulam). CLT elements can be susceptible to delamination of lamellas during fire, giving access to uncharred wood and consequently an increase in fire severity.
Some of these challenges are addressed in guidance documents for fire safety design of timber buildings [10]. However, the constant progression of research dictates a continuous development of guidance documents and legislation that deals with these new challenges including design of tall timber buildings. In the US The International building code [11] is one such example and a guidance document for building compliance of mass timber structures [13] is produced in the UK.

2 FIRE SAFETY DESIGN IN MASSIVE TIMBER BUILDINGS

Sweco has worked with fire safety design in several timber buildings, where the most famous one is Mjøstårnet. Mjøstårnet with a height of 85,4 meters was officially ratified by Council on Tall Buildings and Urban Habitat and Guinness World Records as the tallest timber building in the world (May 2019). The building, located in Brumunddal Norway, is an 18-story mixed-use building, containing offices, apartments and a hotel.
The building is constructed as follows:

- High strength glulam columns, beams and diagonals
- CLT shafts for elevators and stairs
- Wooden decks in the first ten floors (made by Moelven Træ8 floor elements), protected with plasterboards in the ceilings and concrete on the floors
- Concrete slabs in the upper floors for apartments. This improves the dynamic behavior (horizontal accelerations), and the sound insulation between the apartments in the building
- Wooden prefabricated façade elements make up the building's envelope

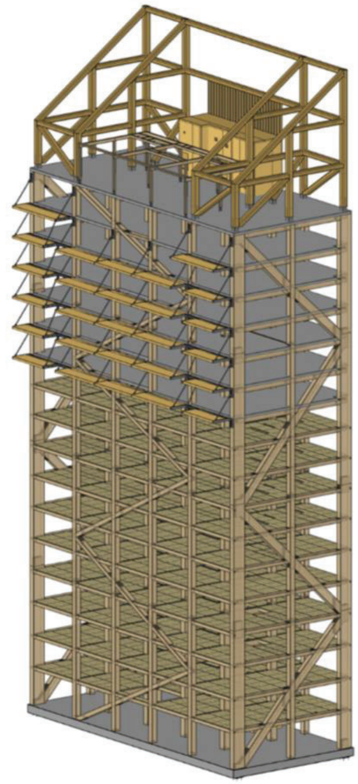

Figure 1: *The structures in Mjøstårnet*

2.1 FIRE SAFETY REQUIREMENT AND APPROACH

The ambition of Mjøstårnet was to build the tallest timber building in the world, with distinct visible timber constructions.
One major hurdle for the project was the fire safety design and its compliance with Norwegian fire regulations.
The regulations require verification that the building will survive a complete burnout without structural failure of the primary load bearing system.
Standard fire safety calculations will not verify neither burnout nor required fire resistance to withstand burnout with combustible construction materials. To address these challenges, an innovative approach was established for the design and verification of legal requirements for Mjøstårnet.

This approach consisted of:

- Prolonged fire testing, including the decay phase, of glulam columns to document the charring rate and the protection of the connections.
- Extending calculation methods for charring rates based on Eurocodes and parametric fire exposure.
- Introducing additional safety measures in the building

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2.2 FIRE TESTING OF GLULAM COLUMNS

To support the analytical design of Mjøstårnet, experiments were set up to study the charring and burning behavior of glulam columns throughout the duration of the fire. Emphasis was made on the decay phase of the fire (Figure 2, and whether charring eventually ceases.

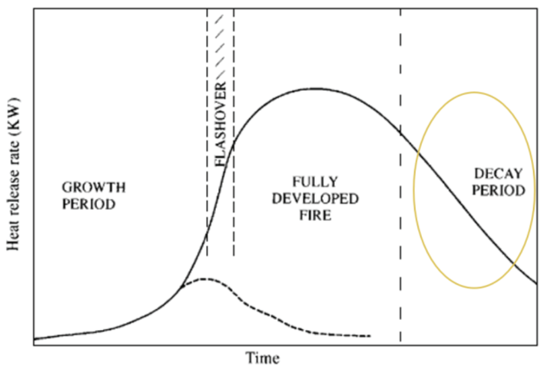

Figure 2: *Heat release including the decay period*

Additionally, the project needed proof that steel connectors were well protected inside the timber. To help answer these questions, full scale testing of three glulam columns was conducted to record the charring behavior of wooden structures with emphasis on the decay period of the fire. The fire tests were conducted by Rise Fire and research AS, together with Moelven and Limtreforeningen.

2.2.1 Findings from the fire tests

3 glulam columns with the measurements of 0,5meter width and depth and a height of 3 meter were used in the fire test:

- 2 identical glulam columns to study the charring and burning behavior throughout the duration of the fire
- 1 glulam column mounted together with steel connectors inside, to study whether steel connectors can be protected inside the timber
- All the samples were mounted with thermocouples inside, measuring the temperature inside the timer construction during the fire test

Figure 3 shows a horizontal cross section of the columns with the thermocouples mounted inside the samples.

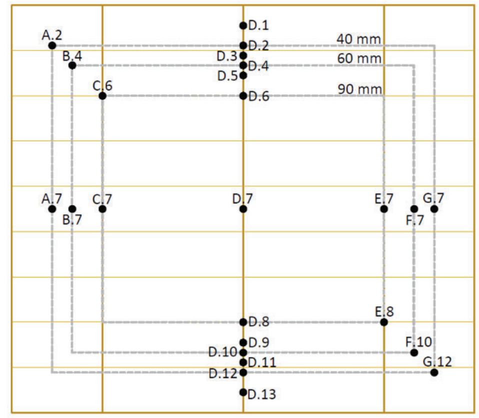

Figure 3: *Thermocouples mounted inside the samples*

The tests were carried out using the ISO 834 temperature curve for 90 minutes. After 90 minutes the burners were turned off. One of the two identical samples (column A) was left inside the furnace to slowly cool for 330 minutes as shown in Figure 4. The other sample (column B) was lifted out of the furnace to cool for 330 minutes in a large laboratory area with natural ventilation from an open door to the outside

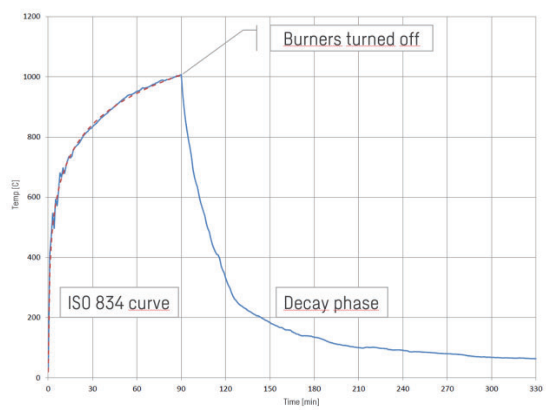

Figure 4: *time/temp curves form the test recorded in the furnace*

These tests showed that the charring rate decreased in the decay period of the fire and eventually stopped. According to Figure 5 the charring reached 40 mm into the columns after 60-70 minutes, 60 mm into the columns after 100-110 minutes, but never reached 90 mm into the columns. In Figure 5 the temperatures 40 and 60 mm into the samples are only shown until the results indicated that the thermocouples begin to loosen (uncertain results when the charring reach the thermocouples). Another interesting result learned from this test is that the temperature in the center of the columns never reached more than 40 degrees Celsius during the 330 minutes the temperatures were recorded.

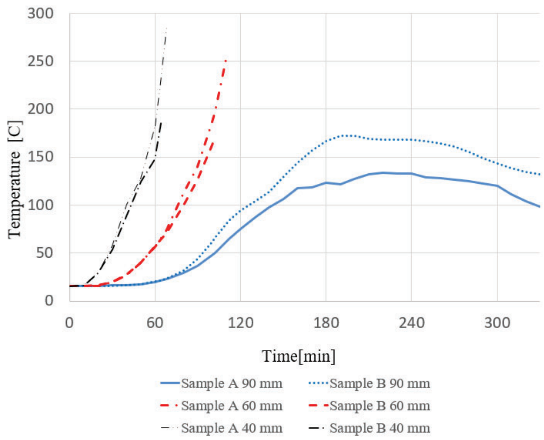

Figure 5: *temperatures inside the columns during the fire test*

At the end of the test (330 minutes with burning and charring) the actual charring depths was measured:

- Column A: 74 mm
- Column B: 71 mm

It was also noted that the actual charring rates in the heating phase were less than notional design charring rates in the Eurocodes. Even though the results might support a less conservative approach the design was made on the safe side according to the Eurocodes.

The steel connectors inside the columns were mounted together with bolts, and the openings were covered using wooden plugs to protect them from high temperatures. In the fire test some of the bolts were left unprotected to study the sensitivity of the solution as well. Figure 6 depicts a vertical arrangement of the bolts and steel plates and the corresponding thermocouples.

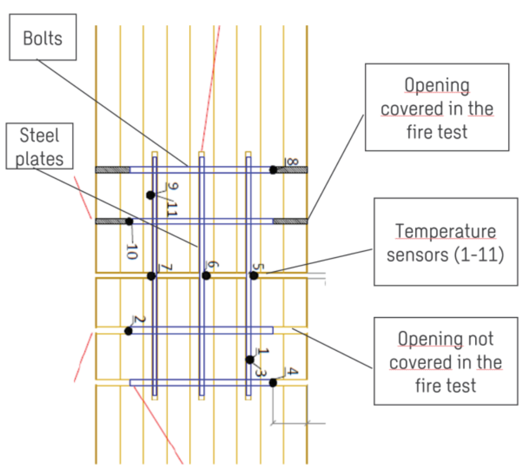

Figure 6: *Steel connectors inside the columns*

The results shown in Figure 7 showed that the steel connectors were well protected inside the timber. The temperatures of the steel connectors never reached more than 270 degrees (C) throughout the duration of the test.

The dotted lines in Figure 7 shows the temperatures of the unprotected bolts (not covered with wooden plugs). It is noted that solid lines, belonging to the temperatures of the protected bolts, did not differ much from the temperatures in the unprotected bolts. In the design of Mjøstårnet, all the bolts were protected. The results from the tests were only used to verify the robustness of detailing, and this indicates that the connectors are well protected, even considering failure in the protection of the steel connectors.

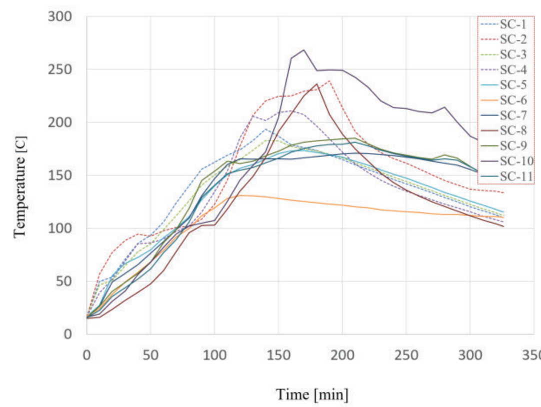

Figure 7: *Temperatures in the steel connectors.*

2.2.2 The heat wave that progresses through the timber

The fire test showed that the charring rate decreased and eventually stopped over the duration of the test. But there is still a heat wave that progresses through the timber after burnout and weakens the uncharred timber to such an extent that failure after burnout is possible. This is an important consideration when designing timber constructions. As structural response of the timber constructions is beyond the scope of this study, only the outlines and conclusion of these considerations are presented here.

Disproportionate collapse due to accident or fire was considered in the structural design of Mjøstårnet. The results from the fire test, measuring temperatures inside timber constructions during a complete fire, was used together with calculation methods from Eurocodes [12] and relevant handbooks[3].

The conclusion is that the timber constructions in Mjøstårnet can withstand a burnout, even considering the heat wave that progresses through the timber after a burnout fire.

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2.3 ANALYTICAL DESIGN WITH WOODEN STRUCTURES BASED ON NATURAL FIRES

Parallel to the full-scale tests, calculations for modeling the full duration of a fire in timber structures needed further development and verification.
Standard design charring rates in the Eurocodes are constant values and do not reflect a fire scenario with a decay phase. The charring rate based on the parametric fire exposure, given in annex a of Eurocode 5 [13], on the other hand considers varying fire severity including the decay phase, using actual compartment geometry. However, the model is based on a constant fire load and gives no consideration of the extra fire load form the wooden structures themselves. The altered method used in the design of Mjøstårnet includes the following steps:

- Based on the parametric fire exposure of Annex A of Eurocode 5, the final charring depth can be calculated together with the corresponding mass of wood contributing to the fire.
- This corresponding mass of charred wood produces additional fire load
- The calculation of the parametric fire exposure is repeated, this time, adding the extra fire load.
- This again will make the charring depth increase and add even more energy to the fire.
- These iterations are repeated, and if they converge, they indicate burnout.

Figure 8 shows schematically the iteration of the parametric time-temperature curve and Figure 9 the corresponding charring depth, according to the methodology described above.

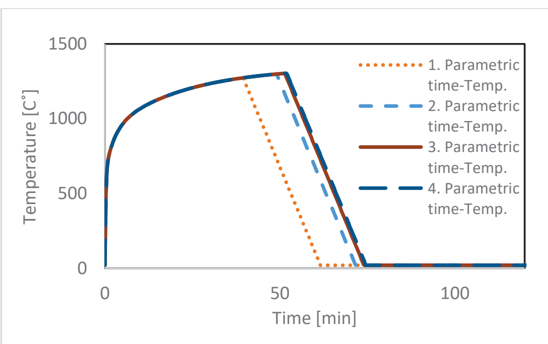

Figure 8: *Parametric time temperature with 4 iterations.*

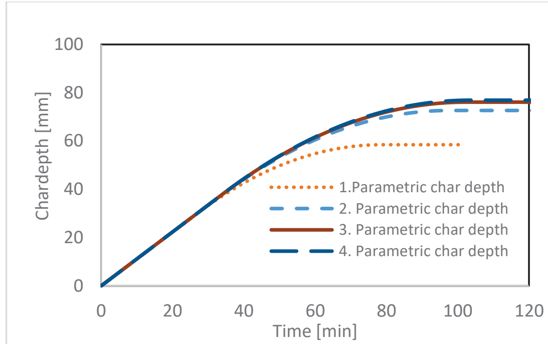

Figure 9: *Parametric charring depths with 4 iterations.*

If the calculations do not converge within reasonable charring depths, they can be repeated reducing the exposed area of wooden surfaces. This makes it possible verifying the acceptable extent of exposed wooden surfaces and at the same time indicating burnout before structural failure.

After the design of Mjøstårnet, similar and improved analytical methodologies are presented by Brandon [14] together with more advanced methodologies that seeks to capture more details of the fire dynamics and material response [8].

2.3.1 Validating the methodology

To validate the analytical methodology used in the design of Mjøstårnet a comparison of experimentally observed charring depths were used. A set of recent experiments where the burning and charring stops after prolonged exposure were selected [9,15-20]. These experiments and their governing parameters are summarized in several recent publications[6,7].

As wood itself is an inhomogeneous material a large scatter of results would be expected. These experiments also contain a broad spectrum of geometries and wooden constructions which would contribute to the uncertainties. Inputs in the calculations are based on values given in the Eurocodes. This means that all wooden constructions area assumed to have a heat of combustion of 17.5 MJ/Kg and a combustion factor of 0,8 with a charring rate of 0,65 mm/min for standard fire exposure. The fire load and geometry are taken from the experiments and the thermal absortivity for the total enclosure is assumed to be 500 $J/s^{1/2}m^2K$. The methodology assumes a one-dimensional charring rate based on the parametric fire exposure over the entire surface of wooden constructions and is iterated as previously explained. Figure 10 shows a plot of measured char depths against calculated char depths. Experiments that significantly exceeds the validation range of relevant parts of the Eurocodes are excluded from the plot. All safety factors in the Eurocode for determining fire load are taken as 1 in these calculations. The calculated results will therefore deviate from the design values.

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The grey line constitutes a perfect match between experiments and calculations and points on the right-hand side will be on the safe-side meaning an overprediction of charring depths.

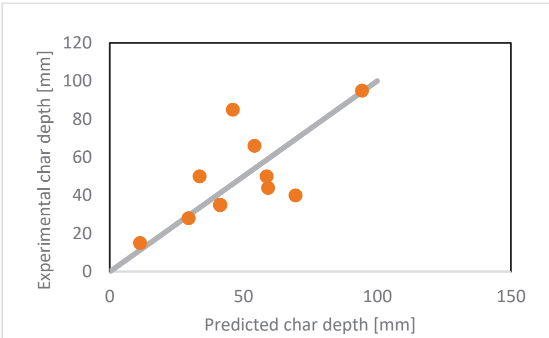

Figure 10 *Predicted vs experimental char depth*

The experiments on the left-hand side which underpredicts the char depths, either experienced delamination of the CLT element or increased charring due to local effects of abutting wooden surfaces. It is also noted that several experiments, all with a large overprediction, are excluded as the time limitations of the parametric charring rate are exceeded.
Considered the validity range of the Eurocodes, the methodology gives a good match between predicted and experimental charring depths.

2.4 ADDITIONAL SAFETY MEASURES IN MJØSTÅRNET

Using an innovative approach for the design and verification of relevant requirements, introduces uncertainties in the results.
To ensure robustness and increase the level of safety for Mjøstårnet, several additional design solutions/fire safety technologies were implemented in the building. Some of them are:

- Loadbearing structures with fire resistance R120 (Designed to resist a burnout with safety margins included)
- Shafts are fire stopped at each floor with fire resistance EI 60
- Sprinklersystem with increased reliability according to EN 12845 Annex F. Hazard class OH3, double water supply, and quick response sprinkler heads
- The water supply to the sprinkler systems is specially designed for Mjøstårnet. In addition to normal water supply, the swimming pool facilities in the building can deliver water to the sprinkler systems. This will secure functionality of the sprinkler, even if the water supply system in the area fail.
- Fire protection of ventilation ducts with incombustible insulation
- No combustible surfaces in voids and technical rooms
- Two pressurized escape stairs
- Automatic fire alarm, which automatically alarms the Fire brigade
- Facilitation for the Fire brigade
    - Firefighting lift
    - Dry risers
    - Control room
- Façade
    - Materials that comply with the requirement B-s1,d0. (Materials that has limited combustibility, low smoke production, no burning droplets)
    - No combustible insulation materials in the building
    - Certain areas of the façade are sprinkler protected (The balconies and façade covered with combustible materials in the two first levels of the building).
    - Firestop in the cavities at each floor. Vertical gaps are thus closed for each floor. In addition, there are fire stops over the windows to further reduce the chance for fire spread in the façade.
    - The risk of fire-spread between different floors in the building is also reduced, introducing balconies and/or vertically distance between windows in different floors

2.4.1 Level of safety in Mjøstårnet

Some of the requirements implemented in this project follows from the Norwegian regulations for buildings of more than 8 floors. These requirements are further combined with additional design solutions/fire safety technologies to ensure robustness and increase the level of safety. Combined with the analytical design methodology used in this project, it's verified that the level of safety in Mjøstårnet meets the requirements following from the Norwegians codes, even when using timber as construction materials.

3 Conclusion

A tall timber building can be designed to resist a complete burnout without failure of the primary loadbearing system at the same time allowing visible timber constructions. Careful considerations of fire behavior, verification methods and additional fire safety measures must build the foundation of such design.

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