FIRE RESILIENCE OF CROSS LAMINATED TIMBER IN RESIDENTIAL BUILDINGS

Exploring a Sustainable Feature

Andrés Felipe Berdugo Calderón

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Preface

Looking back, I realized that timber as a material itself, has been present in my life since I was a child. My father had a furniture factory; he used to bring me there to see how things were made with wood and other tools. He taught me how to saw, drill, glue and paint wood. Of course, I was very young and by no means an expert, but I loved to go to my grandparent's big backyard and start building makeshift wood houses with what I learnt on the factory.

As an architect, it would sound difficult and challenging to select a research topic with such an engineering background. And indeed, it was. However, I recognize myself as someone who dares to accept challenges. The possibility to include timber as the core idea of my final master thesis research, brought me back priceless memories from my childhood and represented the perfect opportunity to understand better such an appealing construction material.

The investigation value then, does not only rely on the opportunity to work in a northern European laboratory or being sponsored by important companies, but rather in the effort to understand and link two disciplines through a material and its properties. Studying architecture, for me represents the opportunity to bring together a human being dichotomy: rational think as science and creative thinking as art sensibility.

Adventuring inside a fire safety laboratory to construct and test with my own hands, represented the pinnacle of my architectural career. Not only did I learn a lot about engineering but also, I was able to understand and use the scientific results to talk about the importance of the aesthetic value of a space based on the finishing material and the sustainable advantage that comes with its usage. Timber then, as a childhood hobby and a construction material, represents an unacknowledged passion in my life.

Andrés Felipe Berdugo Calderón
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This thesis is the result of a long and complex process. I would like to acknowledge those who contributed to make it possible. I would like to thank:

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My Parents for being the most important and unconditional support of my life. This work is the result of our year of struggle. From the abroad, I specially dedicate this thesis to you two.

Vanessa Molina for your unconditional love and support. Without your courage and determination, I would not have even considered the possibility to study abroad. Love you a lot.

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Abstract

An experimental investigation of about self-extinguishment of cross laminated timber (CLT) based on the impact of shifting radiation heat fluxes (Rfx). Initially, the behaviour of four CLT samples, made with two different types of adhesives: Polyurethane (PU) and Melamine (ME); was tested under the same initial condition of 25 kW/m^2 generated by a propane powered radiant panel for up to 120 minutes. These initial samples worked as a control reference to measure the delamination process expected to occur in the engineered timber material.

The second series of experiments, tested three more samples of each adhesive type, starting with the same initial setting of 25 kW/m^2. After 30 minutes, the radiation flux was decreased to three different scenarios: 15 kW/m^2, 10 kW/m^2 and 5 kW/m^2 for up to 60 minutes. Glue layer temperature, front temperature and mass loss rate data were recorded during the experiments. Self-extinguishment could lead to the improvement of the probabilistic lifespan of a building (lower failure probabilities that provide higher reliability) and thus, lay out a fire resilience feature of CLT constructions, linking its usage to a sustainable development.

Abstract (Italiano)

Un'indagine sperimentale sull'autoestinguimento del legno lamellare incrociato (CLT) basata sull'impatto dei flussi di radiazione mobili (Rfx). Inizialmente, il comportamento di quattro campioni CLT, realizzati con due diversi tipi di adesivi: Poliuretano (PU) e Melamina (ME); è stato testato nella stessa condizione iniziale di 25 kW/m^2 generato da un pannello radiante alimentato a propano per un periodo di 120 minuti. Questi campioni sono stati utilizzati come riferimento di controllo per misurare il processo di delaminazione previsto nel materiale in legno.

Nella seconda serie di esperimenti, sono stati testati altri tre campioni di ogni tipo di adesivo, iniziando con la stessa impostazione iniziale di 25 kW/m^2. Dopo 30 minuti, il flusso di radiazione è stato ridotto a tre diversi scenari: 15 kW/m^2, 10 kW/m^2 e 5 kW/m^2 per un massimo di 60 minuti. Durante gli esperimenti, sono state registrat le temperature dello strato di colla, le temperature frontale e la velocità di perdita di massa. L'autoestinguenza potrebbe portare al miglioramento della durata probabile di un edificio (probabilità di guasto inferiori che forniscono una maggiore affidabilità) e quindi, definire una caratteristica di resilienza al fuoco delle costruzioni CLT, collegando il suo utilizzo ad uno sviluppo sostenibile.

PART A.
THEORETICAL FRAMEWORK

PART A. THEORETICAL FRAMEWORK

1. Introduction

Cross laminated timber (CLT) is an engineered timber material that is gaining popularity as a construction material in Europe for residential buildings. As it is produced from a renewable source such as wood, it is commonly labelled as a sustainable material. Amongst residential buildings, CLT is used as both separation constructions and load bearing elements of fire compartments (rooms). However, as a cellulose product, it also represents a risk for being combustible and increasing the fire load of a building, compromising its sustainably performance. Self-extinguishment, a presumed resilient feature based of the charring process of wood, added to a robust design of the Lines of Defence (the normative barrier for fire spread), could lead to maintain the building's functionality after a fire and thus, displaying a characteristic of unprotected CLT to mitigate fire damage.

1.1. Aim

This thesis aims to investigate the fire resilience of unprotected cross laminated timber (CLT) residential constructions, through the alleged self-extinguishment of timber and its labelling as a sustainable feature, based on the probabilistic lifespan method, which assess the robustness and durability of buildings. By improving the normative Lines of Defence (fire spread barriers), it is possible to lower the failure probabilities of the construction and achieve a higher reliability, which can be translated in a longer building lifespan and hence, in a higher resilience indicator.

1.2. Objectives

- Propose an experiment to assess the viability of self-extinguishment of CLT, as a method to enhance LOD1 (Line of Defence: Preventing a Compartment Fire).
- Quantify and assess self-extinguishment of CLT based on the adhesive type and their influence in the lamella char fall-off process.
- Qualitatively assess the effects of LOD's improvement as a method to investigate fire resilience of an unprotected CLT residential compartment.
- Propose a robust detailing able to provide lower failure probabilities thought actual fire compartmentation in LOD2 (Line of Defence: Preventing a building fire).

1.3. Scope

The scope of the thesis is to understand the possibilities to acquire actual fire resilience in CLT residential buildings and to set it as an architectural solution, related to the details and compartment distributions of a CLT house, based on the experiments results and current fire safety solutions. The improvement of LODs through the self-extinguishment study and detailing, aims to promote unprotected visible CLT as a material able to prevent a burndown scenario, giving functional continuity to the building, and thus linking its usage to sustainability.

2. Sustainability and Fire Safety Engineering (FSE)

2.1. Sustainability Concept

The trending of the sustainability term is not a contemporary achievement. The current meaning of the word was coined many years ago as a synonym of sustain: to maintain, to support, uphold or endure (The Shorter Oxford English Dictionary, 1964). Later use of the word in the modern age transformed its use at the point to become a policy concept for a territory development.

The acknowledgment of planetary security was made officially public through the "Report of the World Commission on Environment and Development" in 1987. The so called "Brundtland Report", was one of the first documents of the time to recognise the necessity of an environmental awareness of the planet and thus, proposing a new development model.

The approach of sustainable development then, was born from the famous statement: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland Report, 1987). Under this definition, and within an architectural point of view, mankind should opt for sustainable materials to construct.

Later scientific evidence of environmental deterioration, served as the theorical base to state the main pillars of one of the most accepted definitions of sustainability nowadays. The concept of sustainability under the UN resolution 2005 World Summit Outcome, involves three dimensions: Environment, in which the ecological integrity must be maintained; Economy, as the capacity of countries to maintain their independency and access to natural resources; and Society, as the human right to access to enough resources in order to cover basic necessities. Figure 1. shows the pillars of sustainability as one of the theoretical bases for the thesis research.

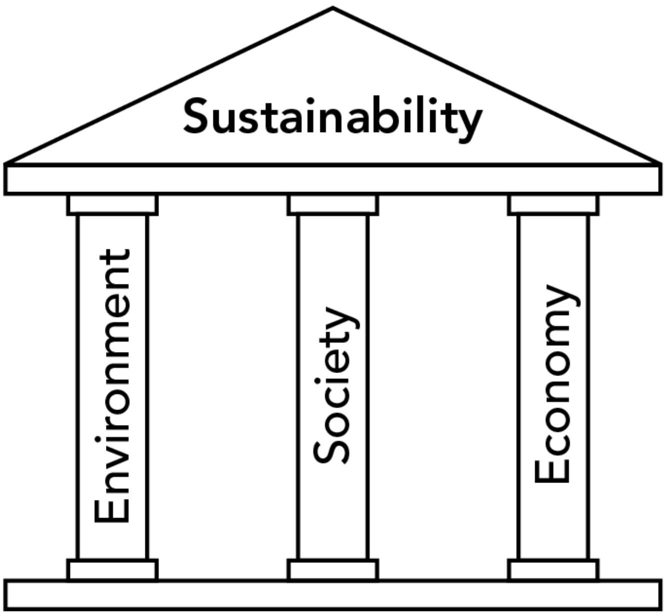


Figure 1. Three pillars of sustainability based on 2005 World Summit Outcome.

2.2. Fire Safety Engineering (FSE)

Talking about architecture and sustainability, the predictable approach for a research thesis would be the one of proposing a project with lower energy consumption that aims to accomplish an Ecolabel standard. A different reflexion on the sustainability concept, led to the interest on investigating about a construction material and its properties to become sustainable. Timber as renewable material with its fire risk weakness, represented the perfect opportunity.

As the research goal was set within a different knowledge field, an interdisciplinary work was needed. Fire safety engineering (FSE) is a discipline that looks after the personal safety of building users, fire fighters and the protection of property; throughout the design of systems and structures that prevent or minimize extreme events related with fires (The University of Edinburgh, 2018). FSE matched as the ideal field to study timber and its flammable feature.

Using a performance-based approach, FSE focus on project specific conditions to define the degree of fire safety of a building as its fire resistance (Van Herpen, 2021). The main factors and conditions that a performance-based approach take into account are shown in Figure 2.

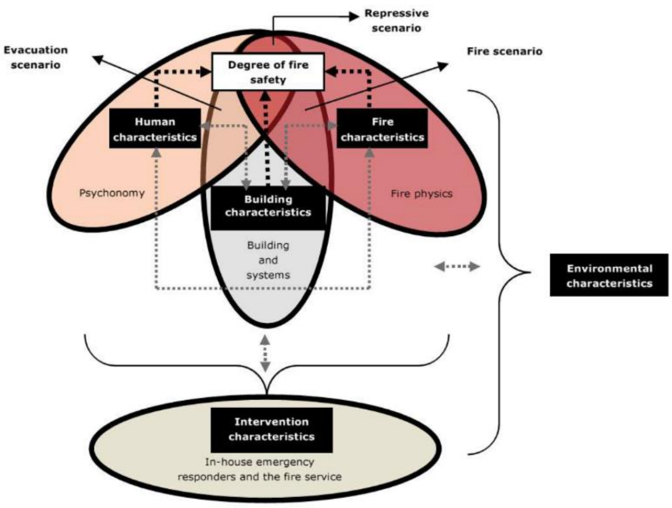


Figure 2. Performance based approach of FSE. (Van Herpen, 2021).

Through the investigation of the (2) fire characteristics present in a fire scenario involving an engineered timber material (cross laminated timber), and the (3) construction characteristics of a proposed fire compartment, the research aims to contribute in understanding timber as a sustainable material, under the resilience concept that will be explained in following sections.

2.3. Physical fire models

Fire models are fundamental part inside fire safety engineering. They describe, under certain parameters, the transport of the source materials in enclosures: fire and smoke. Currently, these models have achieved a software accuracy level, in which fire behaviour can be represented through temperature-time curves. Fire thermal models present a method to solve the thermal and mechanical response of a structure during a fire (Martínez de Aragón et al., 2018).

According to the fire safety engineering methodology, it was necessary to work with a specific fire thermal model in order to understand the response of the investigated material, under the desired experimental conditions. The EN 1991- 1-2:2002 classification for the "Thermal actions for temperature analysis" presents the main models that are explained in the following sections.

2.3.1. Standard Fire Curve

The standard fire curve is the most known fire model amongst the nominal temperature-time curves. It is based on prescriptive rules, meaning that the enforcement of a rule or method is applied. A standard fire curve, normally describes the fire resistant according to a nominal ISO standard curve. As one of the objectives of the research is to set up an experiment to investigate the reaction of cross laminated timber to fire, under specific heat flux conditions that try to trigger self-extinguishment; the restrictiveness of a fire standard model only serves as the initial point to propose an experimental adaptation able to describe a more realistic fire scenario.

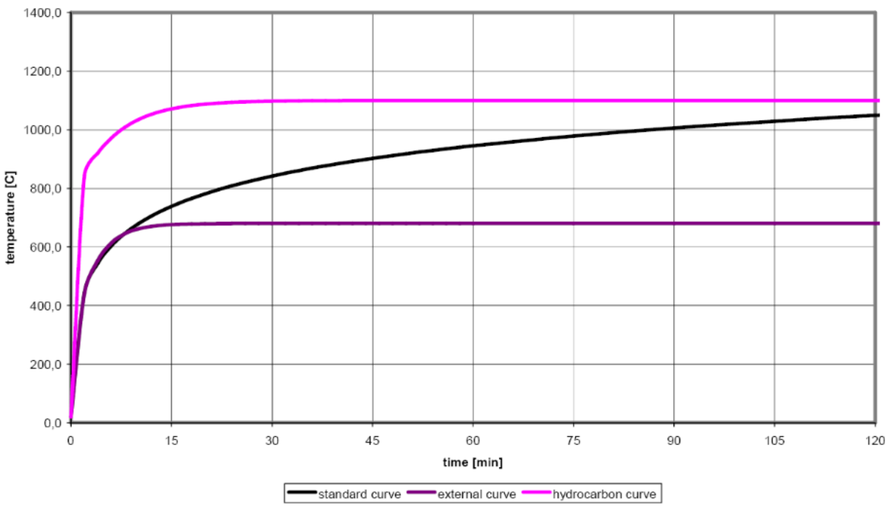


Figure 3. Nominal temperature-time standard curves. (Van Herpen, 2021).

2.3.2. Natural Fire Curve

The natural fire model aims to represent a more realistic scenario of the rate of heat release (RHR) present in a fire. By using simplified fire thermal models and fixed boundary conditions, the natural fire curve fits within a performance-based approach, in which the reaction of a material to certain fire conditions can be studied. In fact, simplified fire models answer to performance-based rules and can be classified in two categories: localized fires and compartment fires (Van Herpen, 2021).

Localized fires are developing fires, present before flashover (fully development of a fire with the most intense heat release). These fires are called fuel controlled, as they depend of the amount of available flammable material. In fire safety engineering, this fire model corresponds to the very first stage of a fire with a possible response through the so-called Lines of Defence 1 (LOD1) (Van Herpen, 2021).

Compartment fires are the fires that remain after the flashover. Oxygen becomes the main actor within the combustion process, as the majority of the fuel was already burnt and the rate of heat release (energy) is reduced and becomes constant. This type of fires usually present external flames, as fire already consumed the material in the enclosure and looks for ventilation. These fires correspond to the response of the Lines of Defence 2 (LOD2) and will be explained in following sections (Van Herpen, 2021).

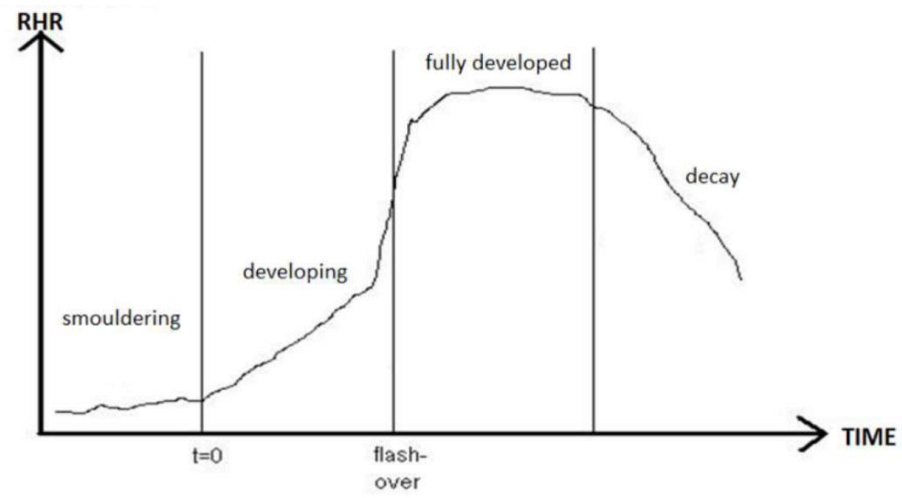


Figure 4. Natural fire curve and its stages. (Van Herpen, 2021).

2.4. Sustainability and Fire

The relationship between sustainability and a complex disciple such as fire safety engineering (FSE), comes from the potential impacts of building fires. Looking outside physical models, fires generally are extreme events with consequences. The identification and mitigation design, of the possible impacts related to fires, through a FSE analysis, can lead to a better management of a material and disclose its sustainable potential.

Under the sustainability concept, fires can trigger three types of impacts. Initially an environmental impact related to effluents and by-products release, soil pollution and infiltration of firefighter's runoff water. A social impact, considering the contamination and destruction of an urban plot, disruptions to the community's life and the shelter loss within a residential fire context. Finally, an economic impact taking into consideration the possible sensible damages and repair costs, financial loss related to property and the time spent for recovery (FSEU, 2020).

The aforementioned impacts, seem to be worse when talking about unprotected cross laminated timber and its flammable character. Despite coming from a renewable source and thus, labelled as a sustainable material, the potential impacts in a fire scenario, and the fire risk itself, tend to overshadow other sustainability benefits of engineered timber products. The mechanical properties of CLT, and its potential to posit a nee a sustainable feature will be explained in the following sections. Figure 5 show the relation between sustainability and FSE.

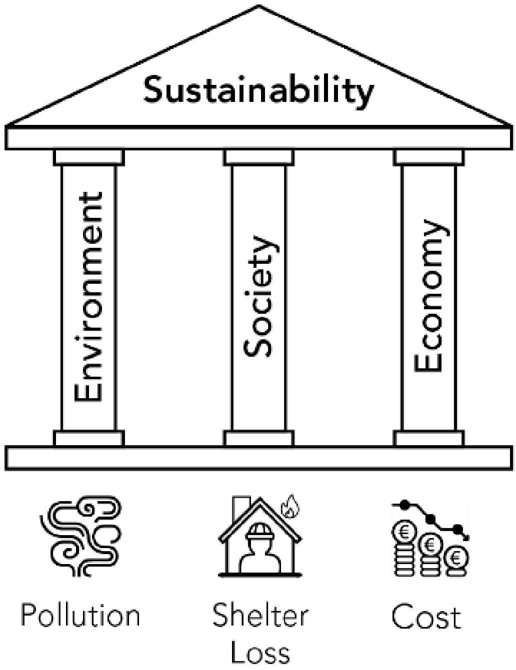


Figure 5. Three pillars of sustainability and their fire impacts.

3. Cross Laminated Timber (CLT)

Cross laminated timber is a construction material comprising at least three layers of glued boards or planks made from coniferous or deciduous wood, with each layer placed at 90 degrees to the next (Gustafsson, 2019). The crosswise arrangement of CLT, helps in increasing the structural strength, load-bearing capacity, dimensional stability and rigidity of the wood panels while reducing their shrinkage and swelling (IMARC, 2021).

The European cross laminated timber market reached a volume of 1.25 million cubic meters in 2020. Due to its prefabrication process, CLT represents an inexpensive, flexible and time-saving substitute to conventional construction materials. The production of standardized dimensions and shapes, allows a reduction of on-site waste and less installation time, converting CLT panels in a very popular material for housing construction in Europe in the last years. (IMARC, 2021).

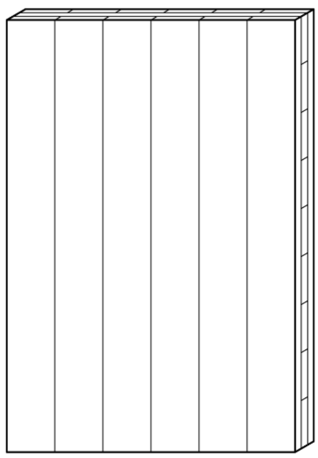


Figure 6. Cross Laminated Timber (CLT) panel.

3.1. CLT production and eco-character

Cross laminated timber is labelled as an eco-friendly material due to its environmentally responsible production and recycle potential. Despite the fire risk aforementioned, that is in fact inherent to any cellulose material, CLT represents a great opportunity for the construction field.

CLT panels are made up of boards or planks with a thickness of 20 – 60 mm. Their raw material is spruce or pine timber, that generally arrives to the manufacture centre, dried and strength graded according to standard SS-EN 14081-1, directly from the sawmill. (Gustafsson, 2019).

After the arrival, individual boards are finger-jointed to create long boards. Once the glue in the finger joints has hardened, the flat sides of the boards are planed and immediately sent for gluing into sheets (Gustafsson, 2019).

The batches of boards are transferred to the gluing line and assembled into large sheets, which are pressed together under the necessary pressure. (Gustafsson, 2019). The most used glues to attach CLT panels are phenolic based adhesives, polyurethane (PU) and melamine (ME), with polyurethane figuring as the most popular in Europe (Brandner, 2013).

The compression process usually uses two methods: vacuum and hydraulic. Vacuum compression provides a steady pressure, even on non-level surfaces, but the pressure is low. Hydraulic compression may involve cold or hot pressing (Gustafsson, 2019).

After the compress-gluing process is done, the final finishing of the components is generally made with a CNC machine, which may also involve sawing edges, milling channels for installations, drilling holes and preparing for joints and fixings. (Gustafsson, 2019). Commonly, the manufacture process of CLT is almost the same despite the place and the production company. An illustrative diagram of this process is shown in Figure 7.

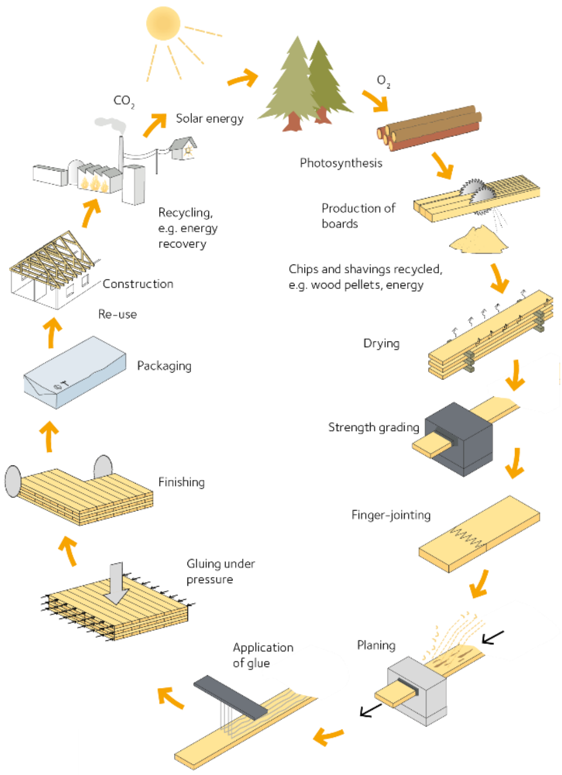


Figure 7. Schematic diagram of the CLT production process. (Gustafsson, 2019).

3.2. Fire Risk of Timber

A previously mentioned disadvantage of timber and cellulose materials, comes to their flammable character that contribute to the fire load of a building. The European reaction to fire classification, according to the standard EN 13501-1, categorizes materials according to the product contribution by its own decomposition, to a fire to which it is exposed. This is not the same criteria that defines if a product is fire resistant (Peroni S.p.a., 2013).

Materials get an initial classification: A1, A2, B, C, D, E and F. Products in classes A1 and A2, are non-combustible, while B to F classes are combustible in ascending order. Materials in A2, B, C, D classes, obtain and additional classification regarding their smoke emission level (s) and the production of flaming droplets/ particles (d) (Peroni S.p.a., 2013).

The European reaction to fire classification places cross laminated timber inside the Euro class D-s2-d0 (Stonko Enterprises, 2016). It means that CLT is considered a combustible material with medium contribution to fire (D), has a level two smoke emission (s2), with a quantity/speed of emission of average intensity, and has no dripping process (d0) (Peroni S.p.a., 2013).

Compared to other materials used as load bearing elements, unprotected CLT will directly ignite after reaching 350 °C (Ravenshorst, 2021). It is known that there are several coating protections that can mitigate the combustible character of CLT, by adding a fire resistance up to 120 minutes. From the architectural point of view, working with timber represents an opportunity to exhibit the wood grain as a finishing material without any type of coating, arguing a fire reliability.

Fire reliability in unprotected CLT, could be obtained through the study of one of the most interesting properties on wood: the charring process linked to the pyrolysis reaction of timber during combustion on a fire scenario. Previous studies investigated the cross-section reduction of CLT beams exposed to fire. After the fire extinguishment, a 7 mm reduction was present, but the centre of the beam conserved the same initial strength thanks to the charring process (Ravenshorst, 2021). Charring then, can act as protection barrier for the inner wood.

If an engineered timber product, such as unprotected CLT is able to withstand fire and then be recovered to some extent, could be called sustainable, as it was able to mitigate some of the impacts of building fires according to the sustainability concept. Such wood property, based on the charring process, can be related to the definition of resilience. Resilience and its theoretical framework and link towards fire safety engineering, will be explained in the following section.

4. Resilience

Resilience according to the Cambridge Dictionary, can be defined as the ability of a substance to return to its usual shape after being stretched, bent or pressed. A more general definition, sets resilience as the quality of being able to return quickly to a previous good condition after a bad situation (Cambridge Dictionary, 2021). A more accurate definition will be explained bellow.

4.1. Resilience in systems

Resilience as a simplified definition can be understood as the state of a system (Haimes, 2006). A further development of the concept, defines resilience as the inherent ability of that system, to withstand a major disruption within an acceptable degradation parameter and to specifically recover within an acceptable time and composite costs and risks (Haimes, 2006).

In that sense, improving the system's resilience implies significant advantages in managing risk, constituting an integral part of the risk management process (Haimes, 2009). A system then, can be characterized by its specific redundancy and robustness. Redundancy is the ability of certain components of the system, to assume the functions of other components that failed, without compromising the performance of the system itself (Haimes, 2009). Robustness then, refers to the degree of insensibility (withstand without compromising the whole integrity) of a system to perturbations or extreme events (Haimes, 2009). This is the initial point to define fire resilience.

4.2. Fire Resilience

Fire resilience, as the concept that meets fire safety engineering (FSE) and the aforementioned definition, can be explained under two approaches. The first one, comes with the concept of functional continuity, described as the ability of buildings to achieve early recovery after fire, by minimizing the extent and degree of damage (Himoto, 2021). Fire Resilience then, can be understood as the measure suitable for evaluating the fire safety performance of buildings, whose functional continuity is required even after a fire event (Himoto, 2021).

The second approach is based in the concept of the probabilistic lifespan (Van Herpen & Van Calis, 2016). Robustness, as the capacity of a structure to withstand a failure event, based on the construction materials and detailing, becomes a key feature to acquire resilience. Building resilience for Van Herpen & Van Calis (2016), is understood as the resistance of a building to special loads or changes as a result of a calamity or extreme event.

Within the investigation context, fire would act as the extreme event. If a building is able to be continued (maintain its functionality) quickly after a fire, it means that there is sufficient resilience in the detailing and materials used. In that way, robustness becomes a sustainable characteristic (Van Herpen & Van Calis, 2016). The complete probabilistic lifespan model and its application will be explained in the following section.

4.3. Probabilistic Lifespan

Robust detailing provides lower failure probabilities, and thus higher reliability which is translated into a longer probabilistic lifespan of the construction (Van Herpen & Van Calis, 2016). As one of the main objectives of fire safety engineering is to prevent, in any case, a burn-down scenario, buildings with a burnout scenario have a shorter probabilistic lifespan than buildings in which the fire has a smaller impact (Van Herpen & Van Calis, 2016).

The probabilistic lifespan of a building can be considered a yardstick for sustainability, as it looks for a better construction method or materials, to prevent and mitigate the effects of fire. Then, it would be right to include fire safety as an assessment aspect in sustainability tools and sustainability labels (Van Herpen & Van Calis, 2016). The probabilistic lifespan offers an opportunity to quantify sustainable fire safety of buildings, especially for those constructed with combustible materials such as cross laminated timber.

Lifespan within the building construction framework, corresponds to the durability and functionality period of the structure before a complete failure. The probabilistic lifespan and specifically, the probability of building failure due to a fire is determined by the failure probabilities of the Lines of Defence in the cascade model (Van Herpen & Van Calis, 2016).

4.4. LOD – Lines of Defence

Lines of Defence (LOD) are the normative barrier for fire spread that must be present in the construction materials and detailing of a building. They are not only related to fire prevention facilities, but also to a repressive action (Van Herpen & Van Calis, 2016). A designed repressive action inside any type of LOD, must support or strengthen the minimum required normative barriers. LODs and their corresponding expected repressive action, are classified as follows:

- LOD0 (Thermally light / Thermally heavy) – A flanking partition construction is necessary
- LOD1 (Local fire); If normative barrier – An offensive interior attack is necessary
- LOD2 (Compartment fire); If normative barrier – A defensive interior attack is necessary
- LOD3 (Building fire); If normative barrier – A defensive exterior attack is necessary

(Van Herpen & Van Calis, 2016)

The failure probabilities of LODs, translated into their impact on the probabilistic lifespan of a building are evaluated as follows:

- LOD0 (Nil) normative; Probabilistic lifespan = building designed lifetime (usually 50 years)
- LOD1 (Local Fire); If there is an instantaneous response (sprinkles) = designed lifetime
- LOD2 (Compartment Fire); If affected = Probabilistic lifespan slightly decreases
- LOD3 (Building Fire – External Repression); If affected = Considerable lifespan decrease

(Van Herpen & Van Calis, 2016)

As previously stated, from the architectural point of view, this research looks for the performance of the material itself (unprotected cross laminated timber) without any type of coating to preserve the finishing value of wood grain. In the same way, an instant response of LOD1, such as sprinkles, is automatically discharged as the addition of this repressive action would just result in the incorporation of a proved mechanism that uses water, putting aside the sustainable yardstick argumentation for the use CLT.

4.5. Cascade Model

The cascade model is the mathematical tool used to estimate the failure probabilities of a building affected by a calamity or extreme event (Van Herpen & Van Calis, 2016). The probability of building failure due to a fire in a given compartment is obtained by adding LODs probabilities:

$$P_{(LOD)} = LOD1 * \{LOD2 + (1 – LOD2) * A_{comp} / A_{build}\} \quad \text{Formula 1}$$

Where:

$P_{(LOD)}$: Total probability of building failure, all LOD's considered
LOD1: Chance of failure of (automatic) repression
LOD2: Fire penetration risk in partition construction (direct + flanking)
A_{comp}: Usable area of the given compartment [m^2]
A_{build}: Usable area of the total building [m^2]

(Van Herpen & Van Calis, 2016)

Formula 1, assumes that a failure of LOD2 automatically leads to building failure, becoming a conservative assumption for buildings with many compartments. The probabilistic lifespan as the result of fire in a given compartment is defined as follows:

$PLT = DLT * (1 - P(_{fi})*P(_{LOD}))$ Formula 2

Where:

PLT: Probabilistic longevity [yrs.]
DLT: design life [yrs.]
$P(_{fi})$: probability of fire in the given compartment
$P(_{LOD})$: total failure probability of all LOD's

(Van Herpen & Van Calis, 2016)

The probabilities of failure in Van Herpen & Van Calis (2016), are defined by the Dutch standard NEN 6079, but can also be obtained from other standards such as IFEG-2005. As the research, will be hosted by a company in the Netherlands, NEN standards will be used as the reference point for the investigation. An illustration of the cascade model is shown in Figure 8.

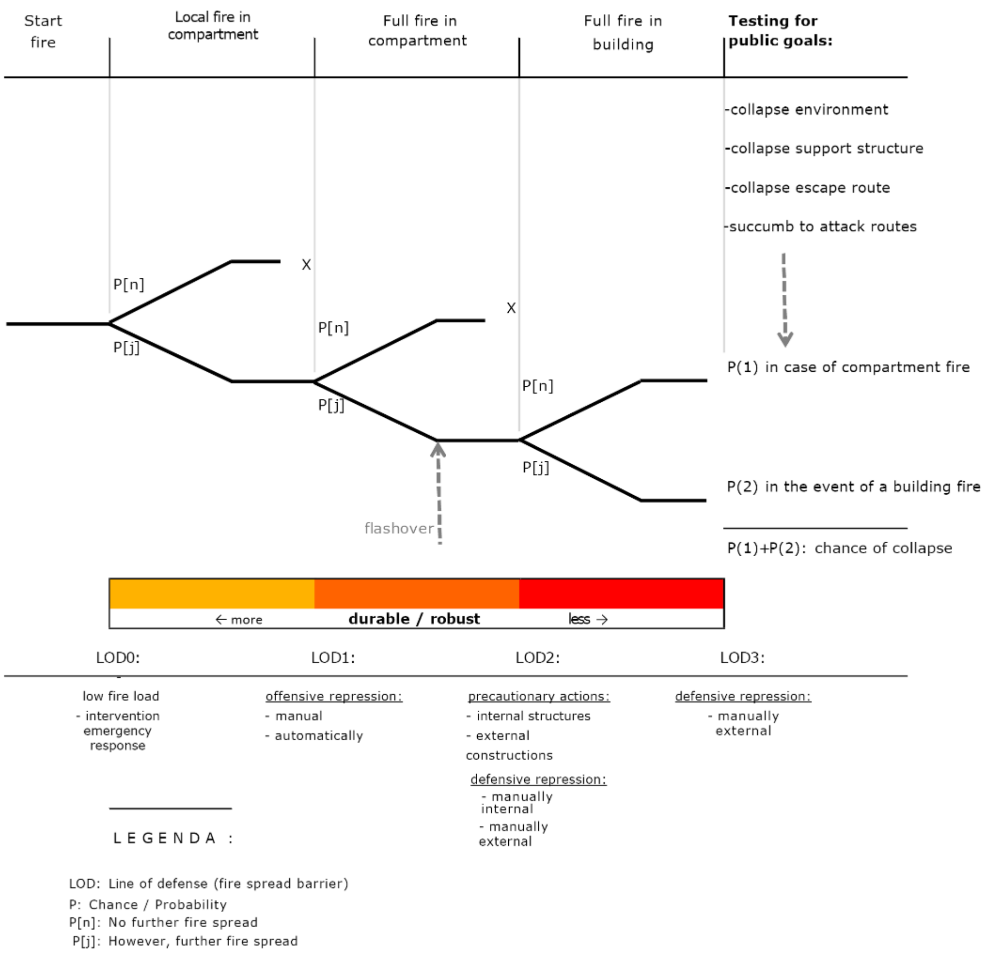


Figure 8. Cascade model with sustainability benchmark. (Van Herpen & Van Calis, 2016).

In the cascade model for fire spread, the farther to the left the normative Line of Defence moves, the smaller the fire size. This increases the chance of a successful fire control, translating into more robustness (Van Herpen & Van Calis, 2016). A benchmark for resilience, as the clear connection with damage limitation, can be assigned to the cascade model. The stronger the initial LOD, the more resilient and thus sustainable, the fire safety concept is and the longer the probabilistic lifespan, enhancing the construction reliability (Van Herpen & Van Calis, 2016).

Strengthen the normative LODs by limiting the fire spread as early as possible, becomes the main objective from the point of view of resilience through acquired robustness. This can be formulated as in Van Herpen & Van Calis (2016), as the main objectives related to fire prevention within the framework of this investigation: Continuity and damage limitation (detailing-related) for LOD 1; and sustainability and damage limitation (building/compartment-related) for LOD 2.

5. Self-extinguishment of CLT (LOD1)

A possible answer to the weakness present as the combustible character of unprotected cross laminated timber (CLT), discarding as aforementioned, an automatic response of LOD1 during a compartment fire, could be self-extinguishment (Crielaard et al., 2019). Self-extinguishment, is a phenomenon that would occur if all combustible contents in the compartment have been consumed and the timber structure is still able to maintain its load-carry strength and is able to provide adequate compartmentation (Crielaard et al., 2019).

A CLT structure might be able to survive fire and prevent a collapse scenario, thanks to the triggering of self-extinguishment. Self-extinguishment was investigated as a passive protection mechanism as in Crielaard et al. (2019), with the possibility to display a resilient quality of engineered timber and contribute to its sustainable character.

5.1. Charr fall-off

Previous investigations such as Emberley, R.L. (2017) have highlighted that self-extinguishment of cross laminated timber compartments, is heavily dependent on the prevention of char fall-off (Schmidt, 2020). The char layer hinders pyrolysis of deeper layers and can thereby starve the fire of fuel after the movable fuel in the compartment has been consumed. The fall-off of the char layer exposes the underlying timber and thereby adds new fuel to the fire (Schmidt, 2020).

According to Schmidt, L. (2020), the forming char layer, product of CLT front side combustions, provides an insulating effect for the timber below undergoing pyrolysis. As a consequence of increased heat losses from the charred surface and a lower heat transfer in depth, the production and mass flow of pyrolysis gases reduces (Schmidt, 2020).

Consequently, a growing and steady char layer will continuously reduce the production of combustible pyrolysis gases in the virgin (unburnt) timber layer (Schmidt, 2020). In this way, the burning rate decreases and delays the onset of pyrolysis in the deeper sections of the CLT sample. Eventually, the formation of a char layer can lead to self-extinction of flaming combustion on the surface (Schmidt, 2020). Burn degradation of timber is shown in Figure 9.

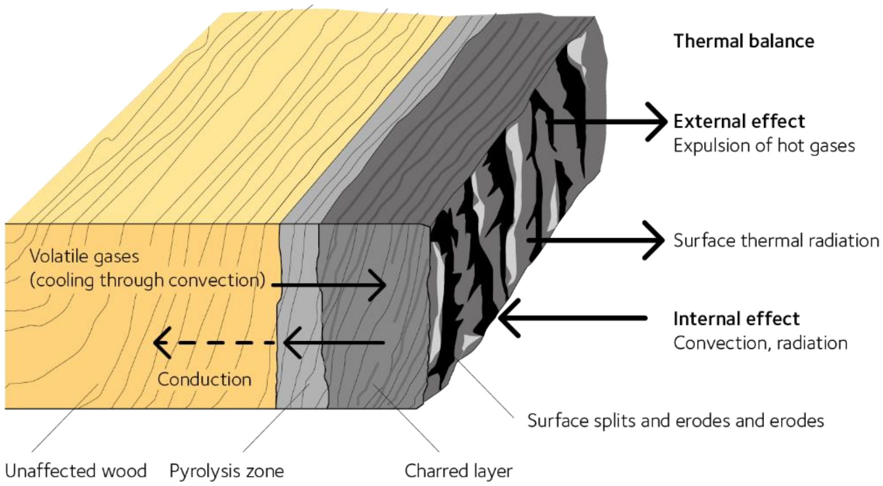


Figure 9. The phenomenon of the charring process. (Gustafsson, 2019).

5.2. Flaming combustion

Combustion can be understood as the oxidation of a fuel (combustible material) by an ignition energy, leading to a lower state of energy level (Van Herpen, 2021). Flaming combustion then, is the process occurring when visible flames and plume of a fire are visible. In flaming combustion, the fuel is present in the gas phase. The reactions and heat release occur in the gas adjacent to the liquid or solid surface (Van Herpen, 2021).

A flaming combustion, triggered by a manual ignition in the front side of the CLT samples, will act as the initial condition of timber combustion for experiments to design, in order to simulate a compartment fire scenario. An image of a flaming combustion is shown in Figure 10.

Figure 10. CLT flaming combustion.

5.3. Smouldering combustion

In the other side, smouldering combustion can be understood as a slow, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel (Ohlemiller, 2002).

According to Crielaard et al. (2019), smouldering was found to be controlled by the rate of diffusion of oxygen to the reaction zone, rather than by the amount of oxygen available in the ambient air. This also suggests that an externally applied heat flux is required to sustain a smouldering combustion with cross laminated timber (Crielaard et al., 2019).

In a real compartment fire scenario, the aforementioned heat flux could be provided by mutual cross-radiation between CLT surfaces and other hot surfaces, such as the flaming or smouldering of room contents (Crielaard et al., 2019). If this heat flux drops below a certain threshold value, the smouldering CLT can be expected to self-extinguish, displaying a fire resilience characteristic. An image of a smouldering combustion is shown in Figure 11.

Figure 11. CLT smouldering combustion.

5.4. Radiation Heat Flux (Rfx)

Heat can be transmitted by three modes: convection, conduction and radiation. Radiation is a significant mode of heat transfer in typical fire environments (Bryant et al., 2003). A radiation heat flux then, can be defined as an external heat transmission mechanism. This external heat source should be provided according to Crielaard et al. (2019), in order to set up the right conditions to investigate self-extinguishment. A schematic setup for testing with (Rfx) is shown in Figure 12.

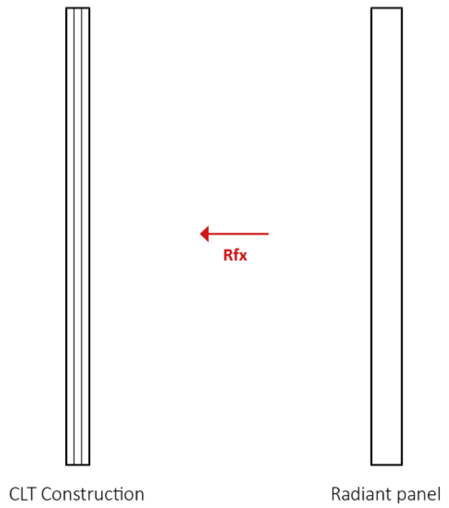


Figure 12. Initial setup idea for the experiments design.

5.5. Model of Self-extinguishment

The key idea behind self-extinguishment is the one that posits that wood is not able to sustain its own combustion, supported by the experience that wood will not burn in flaming combustion unless supported by heat from another source (Crielaard et al., 2019).

Crielaard et al. (2019) proposed a model to reach self-extinguishment. The model is represented as diagram of the expected combustions phases of the engineered timber product. Cross laminated timber then, is expected to either transform from flaming to smouldering combustion, or remain in flaming combustion as a result of fall-off of charred lamellae (Crielaard et al., 2019).

If the fire transforms to smouldering combustion, the CLT might transform back to flaming combustion as a result of fall-off of charred lamellae, continue smouldering if the heat flux received was high enough, or self-extinguish if the heat flux was sufficiently low (Crielaard et al., 2019). The model is shown in Figure 13.

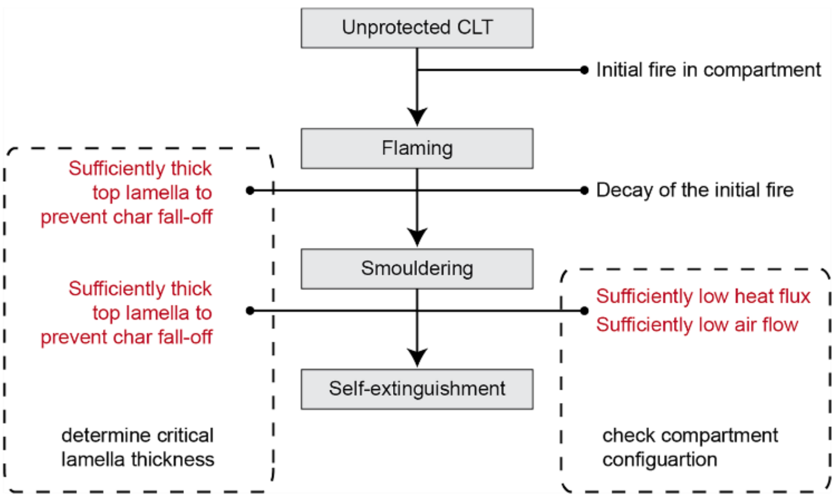


Figure 13. Model of self-extinguishment. (Crielaard et al., 2019).

5.6. Adhesive Type Influence (PU / ME)

A charred lamellae fall-off scenario is a possibility within the self-extinguishment model. A delamination process can imply fall-off of char due to adhesion failure in the char-timber interface or in the timber-adhesive interface (Schmidt, 2020). The adhesive in the glue line might fail and cause separation between the lamellae before the charring front reaches the actual timber-adhesive interface (Schmidt, 2020).

Depending on the progression of the glue failure, this opens the possibility of fall-off of not fully charred timber pieces inside CLT, or even the whole lamella (Schmidt, 2020). This is a benchmark to include the influence of the adhesive type, as an important parameter for the experiment's setup. Wiesner et al. (2021) work with CLT beams, suggests that the use of melamine type adhesives, tend to present a less midspan deflection (mm) when loaded after a fire exposure.

Although the outcomes in Wiesner et al. (2021) are also based on the loadbearing and ply configuration influence, the adhesive type differentiation served as the benchmark to include the glue parameter and its influence to the char fall-off process, to the self-extinguishment investigation of cross laminated timber, as a resilient feature to contribute in the debate of labelling timber as a sustainable construction material in Europe.

PART B.
EXPERIMENTS

PART B. EXPERIMENTS

1. Introduction

The idea of setting up an experiment, was the result of the theoretical framework of Part A. Previous researches and publications suggested that CLT was able to reach self-extinguishment under certain conditions; specially those related to the radiation flux (Rfx) applied to the surface of the material, after the initial flame ignition scenario. Based on the above premise, and the interest of the research team, the search for a testing environment with a reliable company was necessary to design and perform the experiments about fire resilience in engineered timber.

2. Peutz Group – Testing Environment

Peutz is a group of independent consultants founded in 1954. The company specialises in a wide range of fields related to the design and building of any type of architectural or industrial development. Since 1963 has operated as a private company and consists of seven firms with 11 locations across the Netherlands, Belgium, Germany and France.

Peutz operates laboratories for acoustics, building physics, wind technology and fire safety, which are accredited with various standardised measurements, offering quality and high reliability in their consultancy work.

By applying specific project-related research and linking field measurements, laboratory research, numerical simulations and expert knowledge, Peutz brings customised solutions to the market and offered a suitable environment, with their internship program, to construct and develop the experiments needed for this research thesis.

Once the contact was made between Peutz technicians and the research team, it was possible to perform the experiments at Peutz Laboratory for Fire Safety in Mook-Molenhoek, NL.

Figure 14. Peutz Facility in Mook-Molenhoek, NL.

3. DERIX-groep (W. u. J. Derix GmbH & Co.) – CLT Provider

Derix is a German company founded in 1925 in Niederkrüchten-Dam near Düsseldorf. Coming from a family of quality carpentry workers, Derix Group envisions timber as the building material of the future. The production of laminated timber was added to the company's portfolio in the year 1962, becoming long term experts in the production of reliable wood materials.

By using state-of-the-art technology and standardized processes, Derix Group processes certified wood into a load-bearing, flexible building material, from which it produces exceptional glulam timber roof constructions and large-sized, solid X-LAM components. Derix trajectory and vicinity to Peutz labs, represented key features to develop this research thesis.

3.1. Samples

After the initial contact and some meetings, a total of 14 cross laminated timber (CLT) spruce stocks (Skt.) with two different types of glue, Polyurethane Adhesive (PU) and Melamine adhesive (ME) were generously provided by Derix Group. The stocks were prepared to be picked in a Derix hub located in Lierderholthuis, NL.

The following material was collected and brought to Peutz facility in Mook-Molenhoek, NL:

Floor Samples (Horizontal) with **PU adhesive.**

- 4 Stk. L120/3s 300 mm x 600 mm with lamellae of 40 mm (x3)
- 4 Stk. L120/3s 300 mm x 400 mm with lamellae of 40 mm (x3)

Samples (Horizontal and Vertical) with **Melamine adhesive.**

- 1 Stk. L60/3s 400 mm x 800 mm with lamellae of 30 mm, 20 mm and 30 mm
- 5 Stk. X80/3s 400 mm x 800 mm with lamellae of 30 mm, 20 mm and 30 mm

Figure 15. Derix CLT Sample. L120/3s: 300 mm x 600 mm with lamellae of 40 mm (x3).

Figure 16. Derix CLT Sample. L120/3s: 300 mm x 400 mm with lamellae of 40 mm (x3).

Figure 17. Derix CLT Sample. X80/3s: 400 mm x 800 mm with lamellae of 30 mm, 20 mm and 30 mm.

3.2. Specimens for testing

After the arrival and inventory of the CLT samples, a calculation and subsequent cutting process took place in order to standardize the sizes of the test specimens. According to the initial dimensions and the support of the testing apparatus, que samples were cut in equal specimens of 400 mm length for 200 mm height as shown in Figure #, Figure# and Figure #.

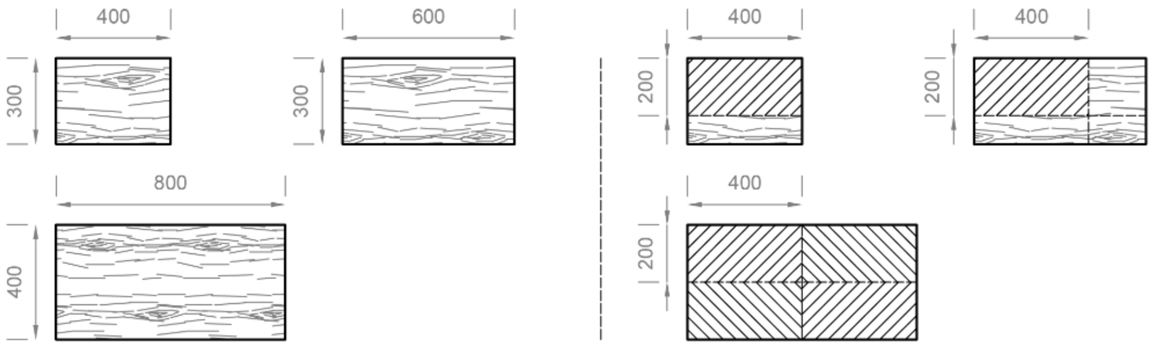


Figure 18. Left – Derix CLT samples original size. Right – CLT samples for testing (400 mm x 200 mm)

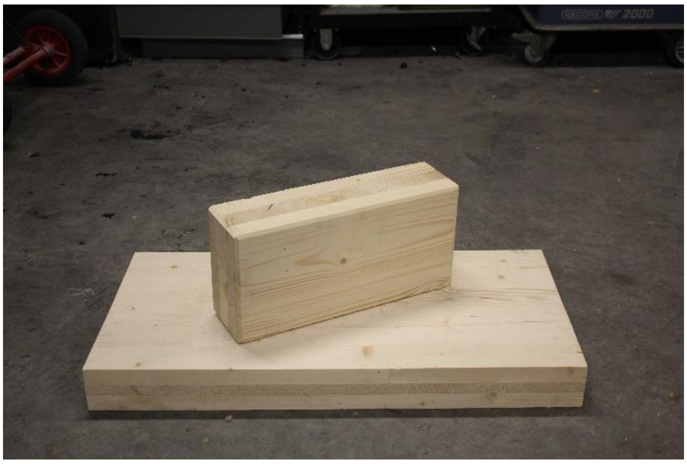


Figure 19. Derix CLT Specimen. L120/3s: 200 mm x 400 mm with lamella of 40 mm (x3).

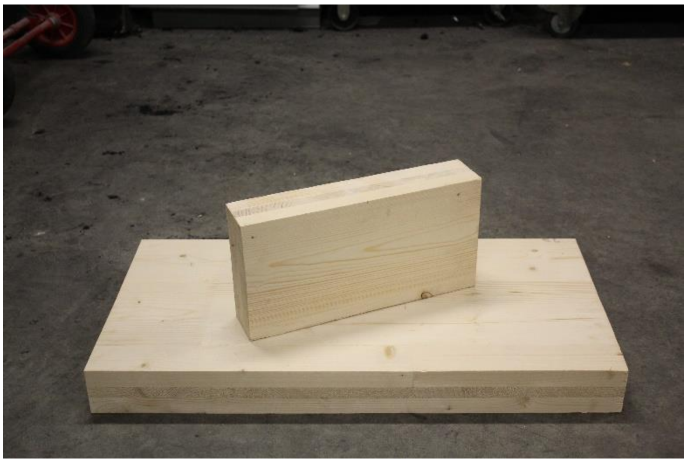


Figure 20. Derix CLT Specimen. X80/3s: 200 mm x 400 mm with lamella of 30 mm, 20 mm and 30 mm.

It was necessary to put a fire insulation material on the samples sides to prevent lateral burning. A layer of Rockwool Soffit Slab with a thickness of 50 mm was fixed with washers. One side of the specimen was left unprotected in order to visualise the charring process of timber during the test. For the first series of experiments, a hole was drilled in the rear side to reach the first glue layer in order to install a thermocouple and measure the glue temperature during the test. Figure X and Figure X show the final version of specimens to be tested.

Figure 21. PU - CLT Specimen. L120/3s: 200 mm x 400 mm with lamella of 40 mm (x3).

Figure 22. ME - CLT Specimen. X80/3s: 200 mm x 400 mm with lamella of 30 mm, 20 mm and 30 mm.

4. ISO 5658-2 Standard Adaptation

Peutz Group was already working on the incorporation of an ISO standard to their consultant portfolio. Thanks to the help of one of the thesis advisors, it was possible to participate in the implementation and then adapt the ISO standard to perform the desired research tests.

4.1. ISO 5658-2

Originally named as: Reaction to fire tests – Spread of Flame – Part 2: Lateral spread on building and transport products in vertical configuration, ISO 5658-2 deals only with a simply representation of a particular aspect of the potential fire situation typified by a radiant-heat source and flame ignition (ISO Standard No. 5658-2:2006).

The standard scope consists in providing a testing method for measuring the lateral spread of flame along the surface of a specimen of a product orientated in the vertical position. The data obtained is suitable for comparing the performance of flat materials, composites or assemblies, such as Cross Laminated Timber, that are used primarily as the exposed surfaces of walls in buildings (ISO Standard No. 5658-2:2006).

The test method consists of exposing conditioned specimens in a well-defined field of radiant heat flux and measuring the time of ignition, the lateral spread of flame and its final extinguishment. A test specimen is placed in a vertical position adjacent to a gas-fired radiant panel where it is exposed to a defined field of radiant heat flux (ISO Standard No. 5658-2:2006).

The standard offered some characteristics that could be used to design a suitable experiment for the thesis research. The radiant panel with a measure of 480 mm x 270 mm was able to provide a constant radiation flux (Rfx) of Minimum (Rfx) = 0 - 1.5 ± 0,3 kW/m2 - and Maximum (Rfx) = 50 ± 0,5. It was perfect to simulate the constant and then shifting radiation flux needed to apply in front of the specimens. Figure X and Figure X shows the original setup of ISO 5658-2.

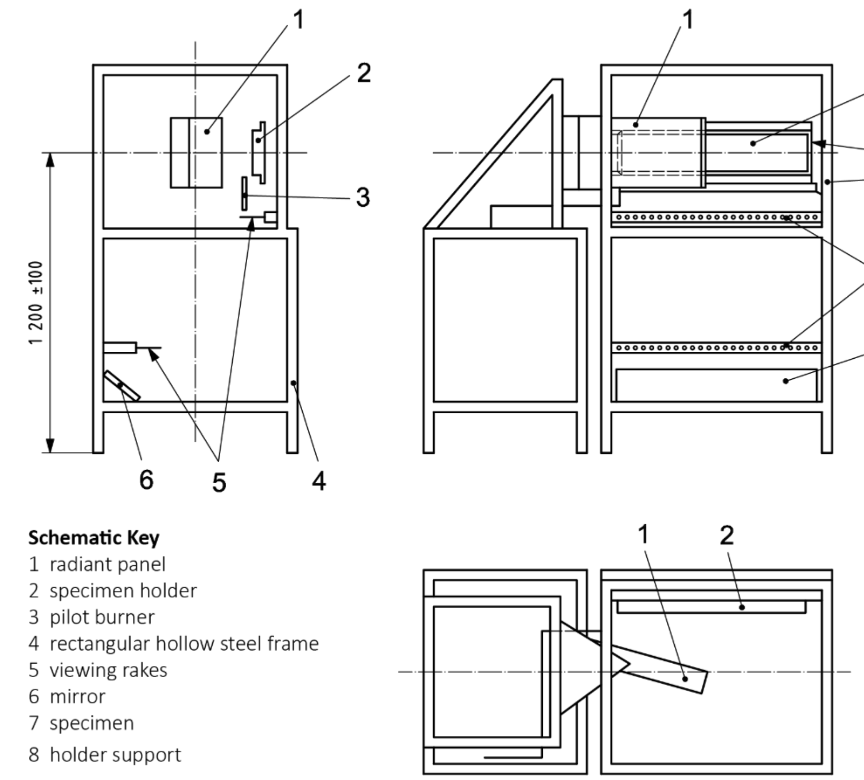


Figure 23. Test Apparatus for ISO 5658-2. Dimensions in millimetres. (ISO Standard No. 5658-2:2006).

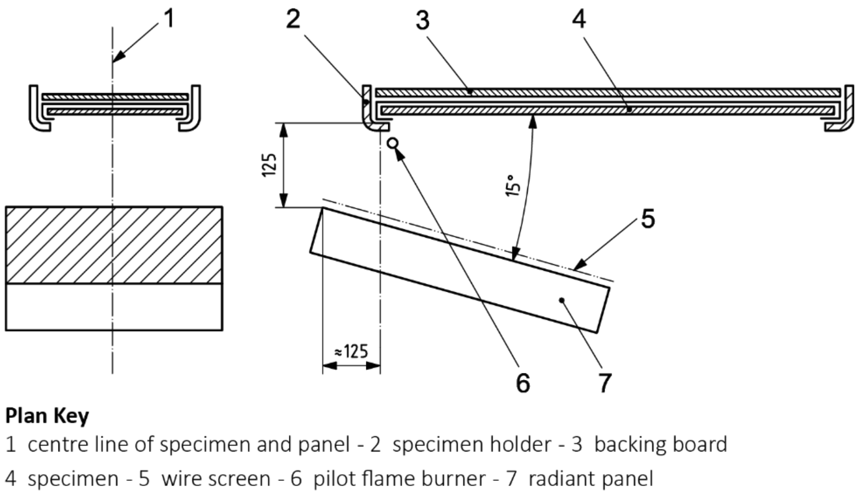


Figure 24. Original radiant panel orientation (15º) for ISO 5658-2. (ISO Standard No. 5658-2:2006).

The specimen holder for ISO 5658-2 was originally designed to support samples of 800 mm x 155 mm x 50 mm. In order to achieve a real and uniform radiation flux in front of the CLT samples, it was necessary to cut the specimens to be smaller than the total area of the radiant panel (Figure X). As the research thesis aims to investigate the self-extinguishment of cross laminated timber and not the flame spread, in the following section the complete adaptation of the ISO Standard and the construction of the experiment will be explained and detailed.

5. Experiments Setup

As mentioned in the previous section, Peutz Group was in the initial stage of constructing and implementing the ISO Standard and the test apparatus was not was not fully assembled. With the help of some technicians from the Peutz Laboratory for Fire Safety in Mook-Molenhoek, NL; it was possible adapt some of original setups and to construct the right apparatus for our tests.

Two series of experiments were planned. The first one aimed to investigate the delamination process of cross laminated timber through the exposure of the specimens to a constant radiation flux (Rfx) of 25 kW/m^2 for up to two hours. As the initial heat flux was not enough to ignite the samples, a manual ignition after two minutes was performed in both experiments. The first series worked as control tests to analyse if the specimens could bear a higher Rfx for a long time before experiencing any char fall-off. A thermo couple was placed inside the specimens to control the first glue layer temperature and its influence in a possible re-ignition scenario.

The second series of experiments consisted in setting up a possible scenario to trigger a smouldering phase and potentially self-extinguishment. After an initial exposure of 30 minutes to a constant Rfx of 25 kW/m^2, the radiation flux value was lowered to 15, 10 and 5 kW/m^2 to investigate the CLT reaction. The thermocouple sensor was placed in front of the specimens to control the front temperature to evidence a possible decrease due to self-extinguishment.

5.1. Radiant Panel orientation

In order to achieve a constant radiation flux coming out the radiant panel, it was necessary to change the 15° degrees deviation from the original ISO 5658-2 Standard. The cold-rolled table in which the radiant panel was fixed (already with the 15° degrees deviation), was turned and aligned to 0° degrees to get a parallel position with the CLT specimens as shown in Figure X.

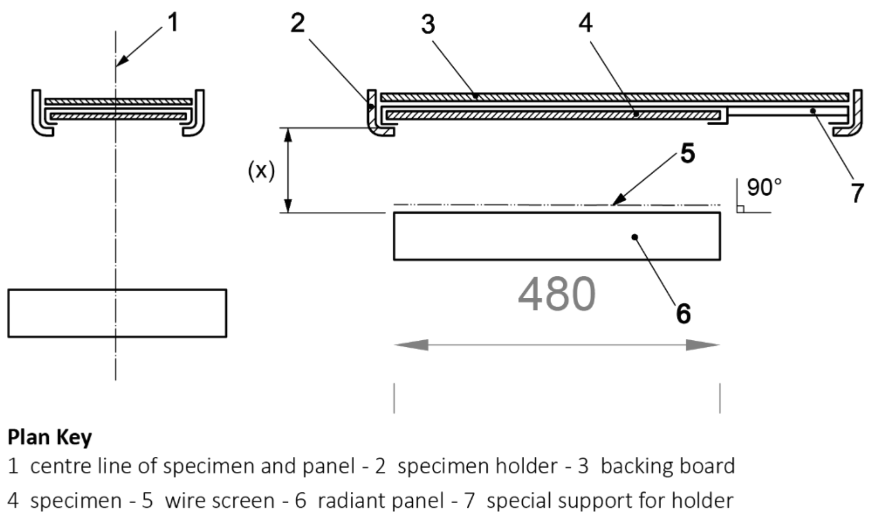
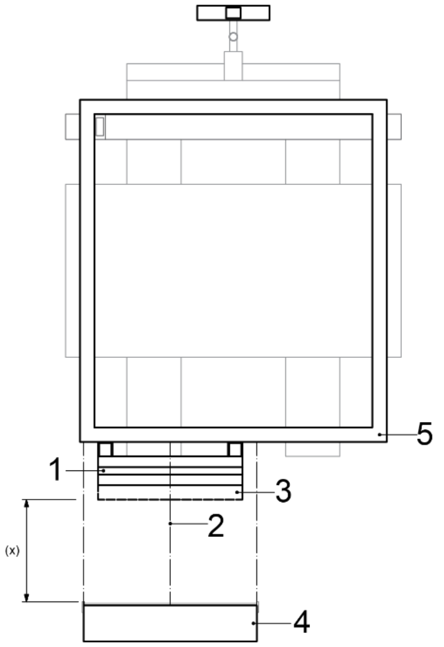


Figure 25. Radiant panel orientation (0º) for Fire Resilience of CLT experiments.

Since the measure of the specimen had to be reduced to fit inside the total area of the radiant panel, the original specimen holder from ISO 5658-2 had to be re-built f. Following the advice of Peutz technicians, the wire screen (5) was substituted with a series of horizontal metal bars. For the second series of experiments, the distance (x) between the radiant panel and the specimen changed from a fixed value to a variable depending on the necessary radiation flux (Rfx) to test with. A record of photos every 6 minutes was set to document the charring in both experiments.

5.2. Specimen holder

As the specimen required a smaller dimension to be aligned inside the area of the radiant panel, a new specimen holder was needed. Starting from a cold-rolled table made with square profiles (40 mm x 40 mm), it was decided to simplify the holder by attaching two rack profiles with a gap of 400 mm to fit the length of the specimens. The new holder is described in Figure X.



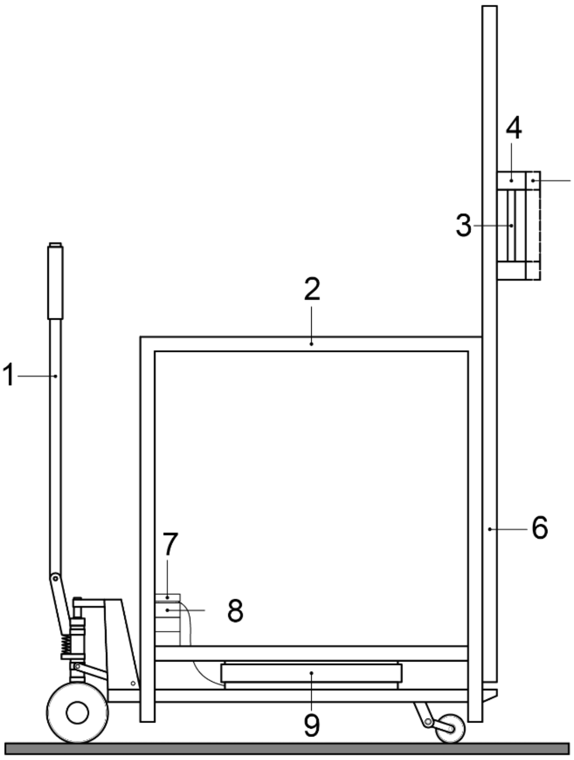
Plan Key
1 CLT specimen- 2 centre line of specimen and panel
3 PU specimen projection - 4 radiant panel - 5 new specimen holder

Figure 26. New specimen holder constructed for Fire Resilience of CLT experiments.

In order to test at different radiation fluxes without compromising the exact gas flow coming from the propane bottles, and to be accurate, it was necessary to design a movable specimen holder able to reach different distances (x) among the radiant panel and the CLT specimens. Figure X explains the design of the new specimen holder (5) mentioned in Figure X.

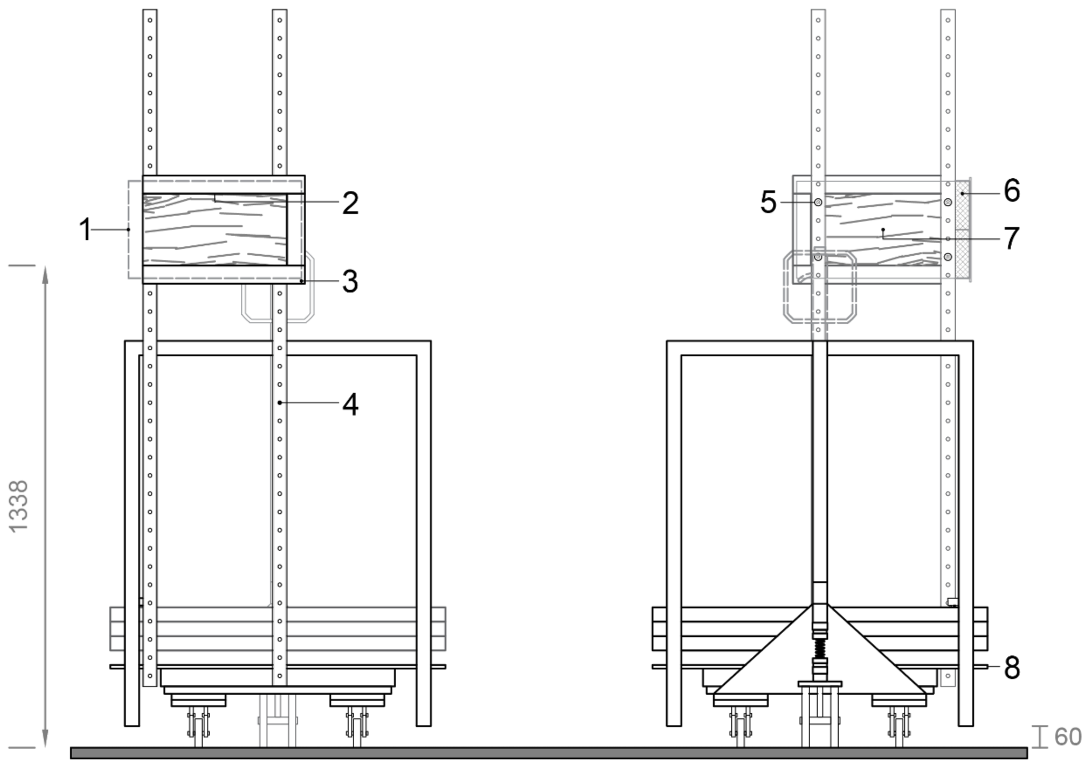
Thanks to the suggestion of one of the thesis advisors and following the material properties, it was decided to also record data related to the pyrolysis process of timber in the form of mass loss during the burning test. Since Peutz Laboratory for Fire Safety did not count with a special equipment to measure mass loss, it was necessary to add a primitive but efficient weighing method to the new specimen holder. A weighing scales was put above a pallet truck, right in the point to be align with the centre of mass of the cold-rolled table with the rack profiles.

A counterweight made with three wood profiles of section 70 mm x 40 mm, was placed in the opposite side in which the specimens were going to be placed. Once the cold-rolled table was in place with the counterweight, a tare function in the weighing scales was active to get an initial value of zero. At the time the CLT specimen was fixed to the holder, the value in the weighing indicator showed just the weight of the specimen. The complete holder with all the adaptations to measure mass loss and acquire different radiation fluxes, is shown Figure X and Figure X.



Elevation Key
1 pallet truck - 2 cold-rolled table (40mm x 40mm) - 3 CLT specimen
4 Rockwool insulation - 5 PU specimen projection - 6 rack profile (40mm x 40mm)
7 weighing indicator - 8 wood counterweight - 9 weighing scales

Figure 27. New specimen holder constructed and adapted for the desired data collection.



Front Elevation Key
1 radiant panel projection - 2 thermocouple sensor (for Rfx shifting tests)
3 Rockwool insulation (50mm) - 4 rack profile (40mm x 40mm)

Rear Elevation Key
5 fixing screw and washer - 6 radiant panel
7 hole for thermocouple (for glue layer tests) - 8 support plank

Figure 28. Detailed elevations of the constructed specimen holder. Dimensions in millimetres.

5.3. Measurement plan and mechanism

A calibration with an infrared radiation sensor was necessary to warranty reliable distances for different radiation fluxes and an equal testing environment for all the CLT specimens. Figure X, illustrates the calibration process made with the infrared sensor.

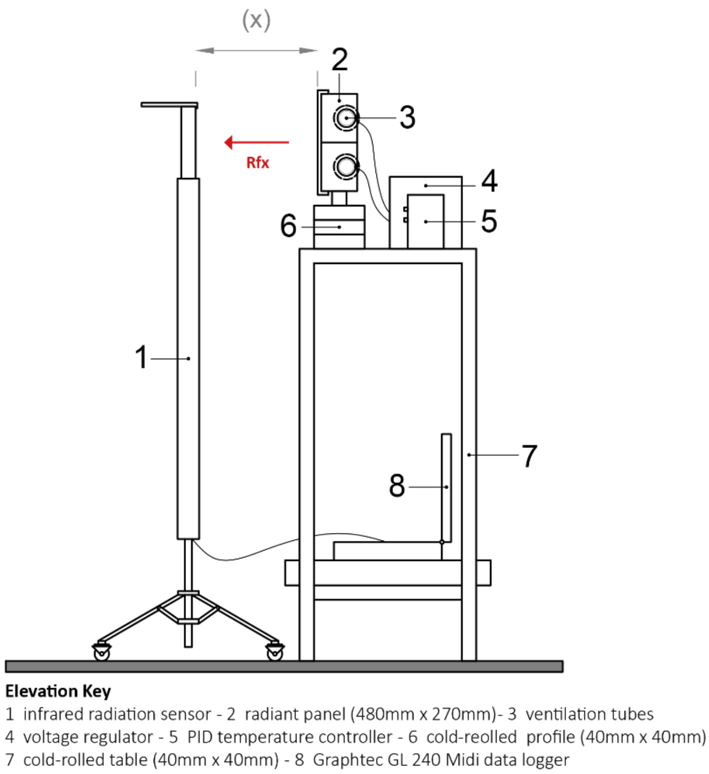


Figure 29. Calibration process to define distance (x) between the radiant panel and specimen holder.

Four distances (x) were recorded and corroborated to obtain the desired radiation fluxes for testing: 220 mm for 25 kW/m^2; 340 mm for 15 kW/m^2; 420 mm for 10 kW/m^2 and 640 mm for 5 kW/m^2. Figure X shows the Data logger used to record radiation fluxes. Figures X, X, X and X shows the final setup with the distances between the specimen holder and the radiant panel.

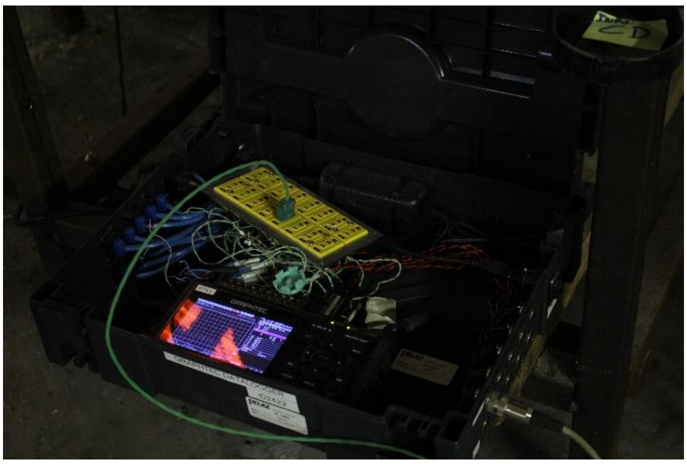


Figure 30. Graphtec GL 240 Midi data logger used to record radiation flux and thermocouple data.

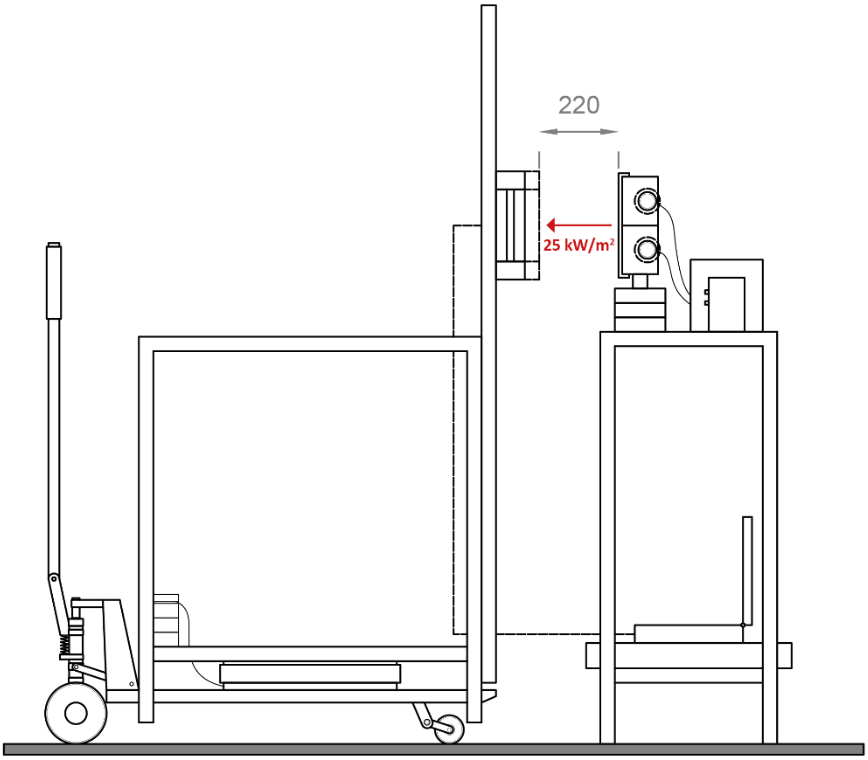


Figure 31. Setup for the initial part of the test. 220 mm for 25 kW/m^2.

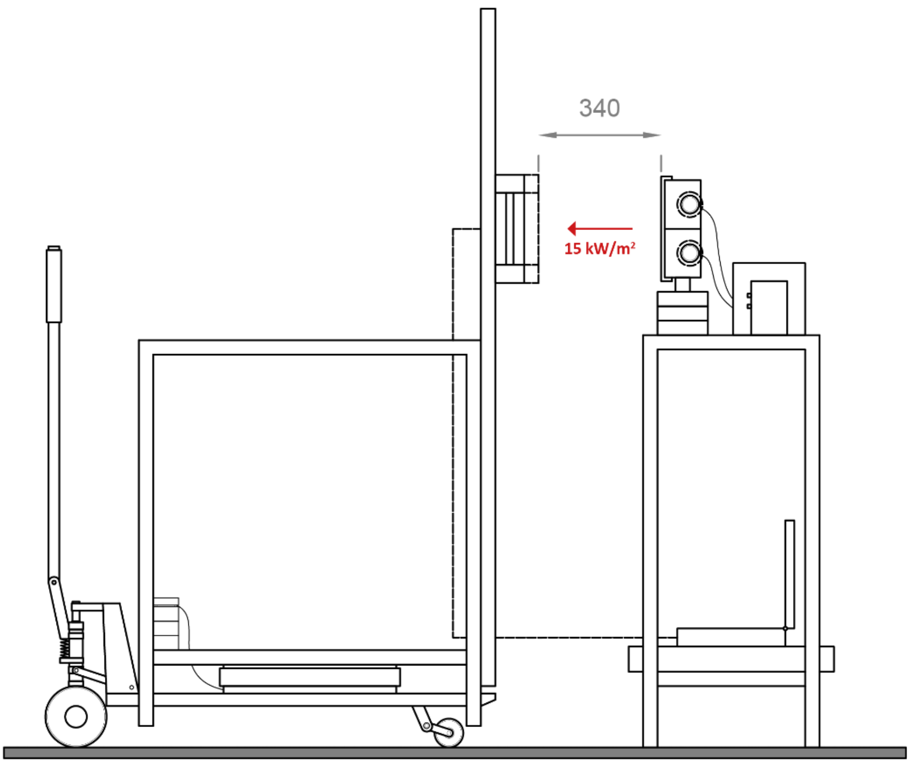


Figure 32. Setup for the shifting experiments. 340 mm for 15 kW/m^2.

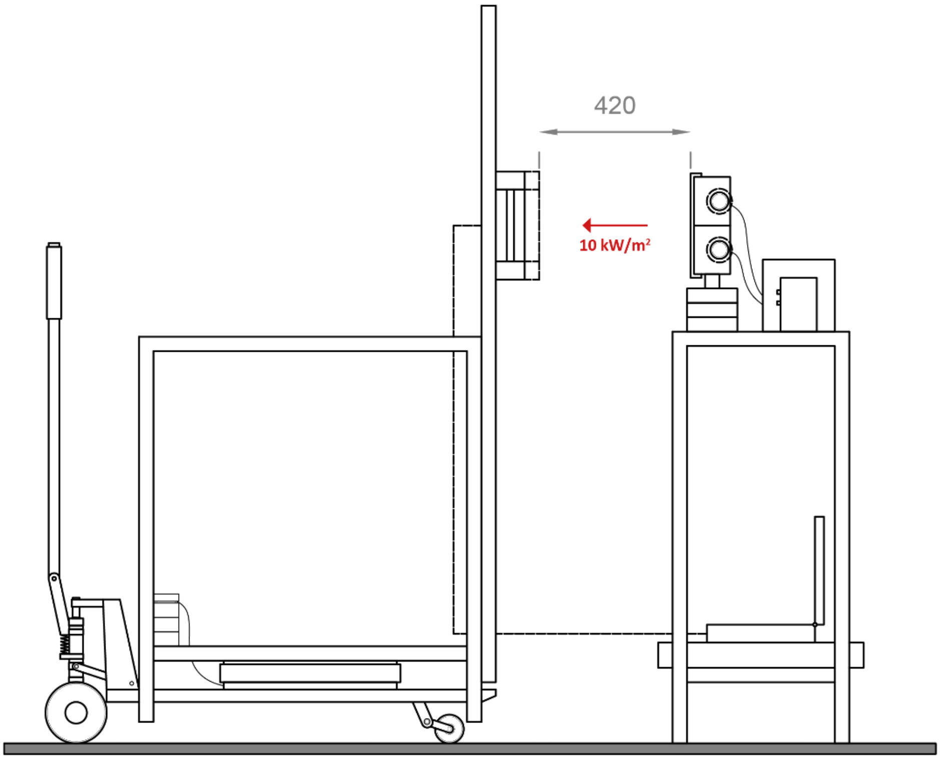


Figure 33. Setup for the shifting experiments. 420 mm for 10 kW/m^2.

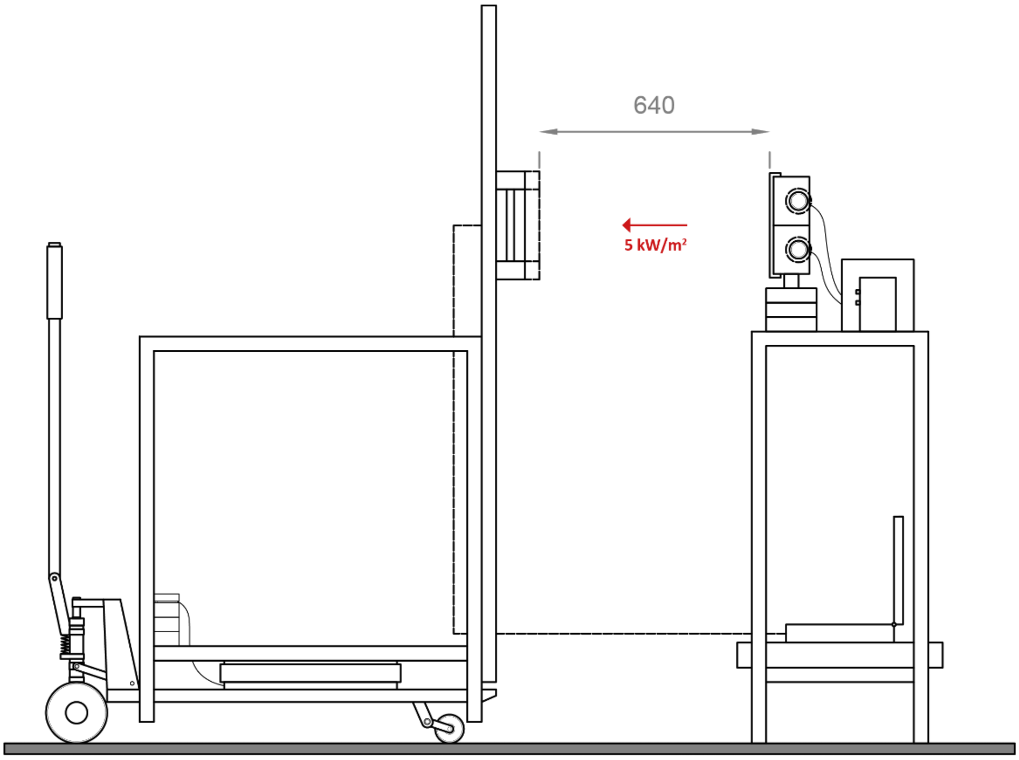


Figure 34. Setup for the shifting experiments. 640 mm for 5 kW/m^2.

5.4. Final Setup and testing images

The final testing environment was achieved after one week of construction, adaptation and some initial tests to verify that all apparatuses worked. Due to the high work flow inside Peutz Laboratory for Fire Safety, the experiment setup had to be moved from one side to another of the laboratory. The following Figures show both locations and some photos during the tests.

Figure 35. Setup on side A (left side of the laboratory). 20/12/2021

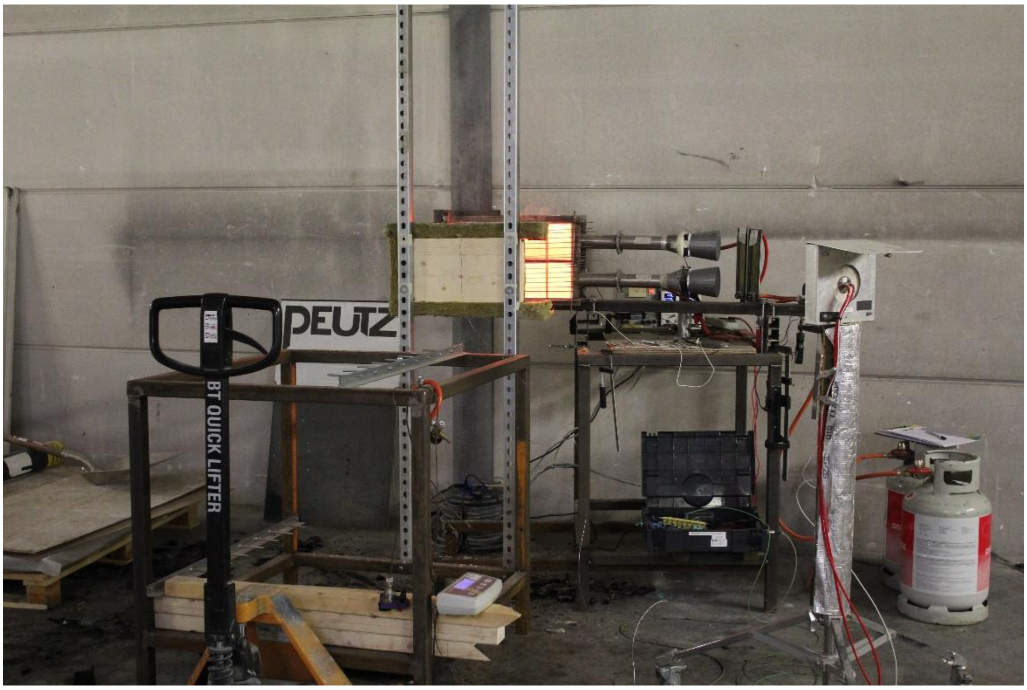


Figure 36. Setup on side B (right side of the laboratory). 23/12/2021.

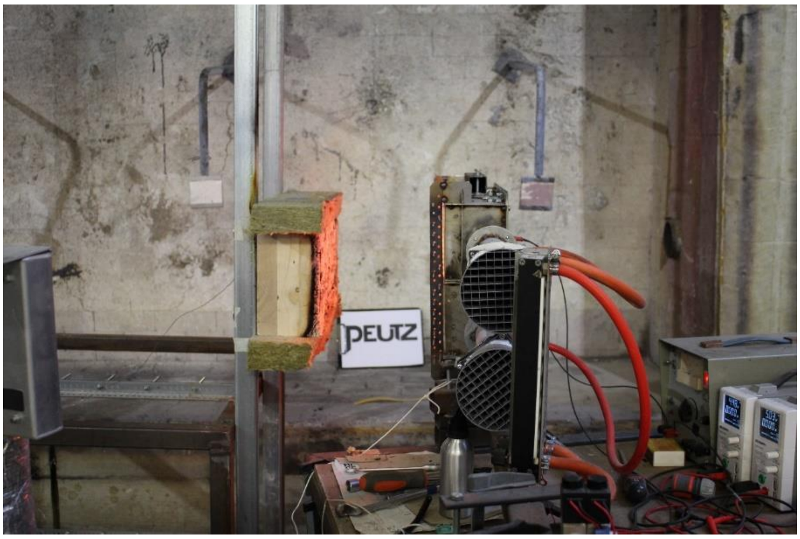


Figure 37. Testing on side A. PU 1 - 20/12/2021.

Figure 38. Setup on side B. ME 2 - 21/12/2021

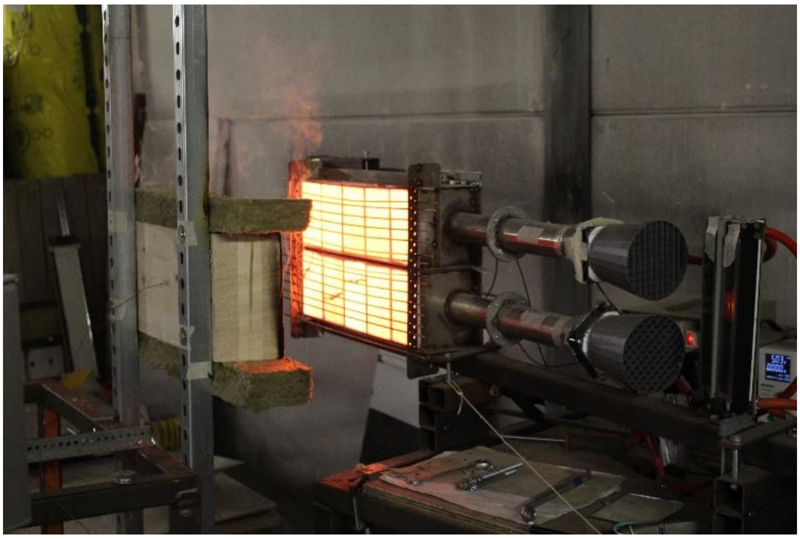


Figure 39. Testing on side B. PU 2 - 21/12/2021.

6. Results

As aforementioned, a sequence of photos took every 6 minutes was made to document the charring process in both series of experiments. Temperature data in the glue layer and in the front of the sample as well as the mass loss, were also recorded for each experiment objective.

6.1. PU Delamination Control Specimens

First series of experiments. In order to investigate the delamination process on the CLT samples made with PU (Polyurethane) adhesive, these series used a constant radiation flux for two hours.

6.1.1. PU 1: 25kW/m^2 for 120 minutes

Time-lapse of the charring process every 30 minutes and the time of the re-ignition.

Figure 40. Time-lapse PU 1. 25 kW/m^2 for 120 min. Re-ignition at minute 76.

The specimen had an intense flaming combustion after the initial ignition, decaying after 6 minutes. Horizontal cracks, following the wood grain appeared in the front of the sample at minute 8. The remaining flames lodged in the described cracks and continued to fade until a smouldering phase was reached at minute 28. First lamella complete visual charring occurred at minute 72. Just four minutes later, a re-ignition with visible flames occurred. First lamella complete fall-off took place at minute 90. After that the specimen continued burning with a decaying flaming combustion until a smouldering combustion was reached again at minute 116.

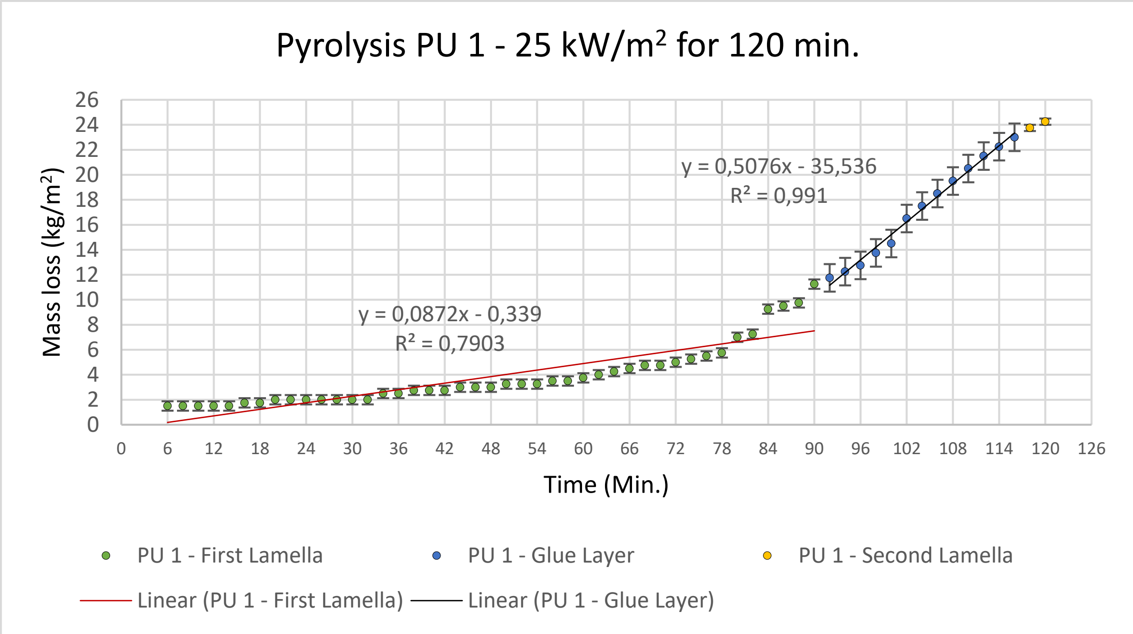


Figure 41. Mass loss per unit surface area graph for specimen PU 1.

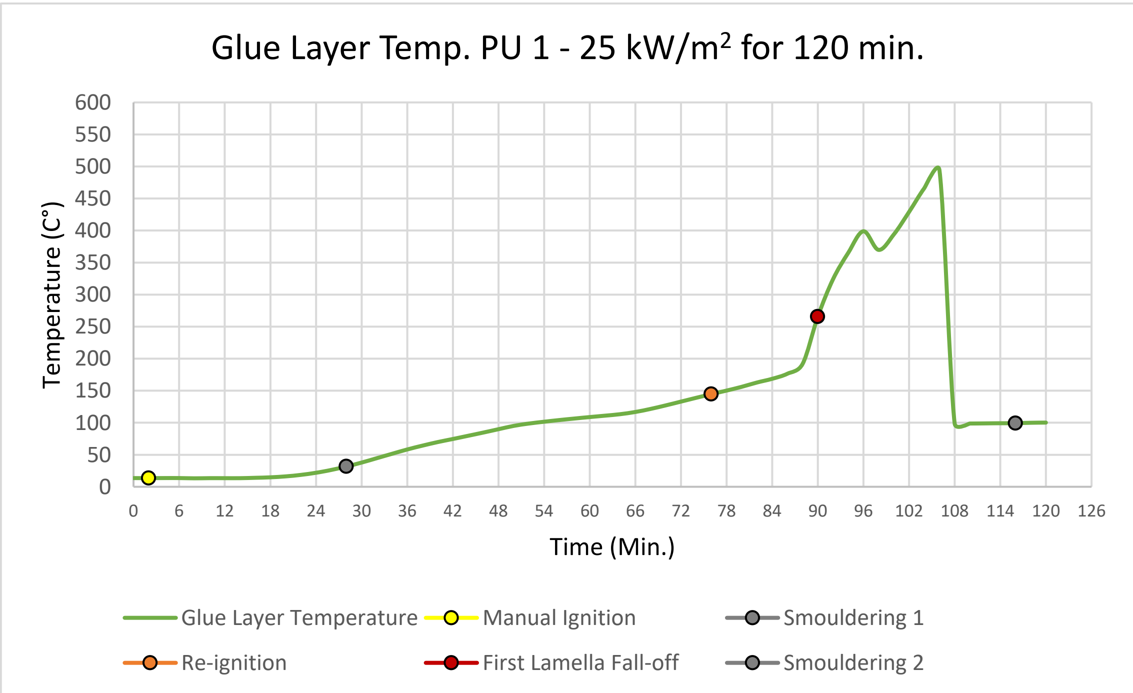


Figure 42. Glue layer temperature graph for specimen PU 1.

Polyurethane adhesive CLT specimen number one (PU 1), presented moderate mass loss rate right up to minute 78. After the re-ignition with visible flames, the mass loss rate increased until the complete first lamella fall-off at minute 90. The ignition of the complete PU glue layer was set to be around minute 86 as the recorded temperature rapidly increased from 176 °C, peaking to 493 °C due to flaming combustion at minute 106. A considerable decrease of the temperature was evident after minute 106; after this point the thermocouple previously installed inside the sample, got completely exposed to external conditions and the measurement got compromised as the sensor started to cool down due to the lack of material in front of it.

6.1.2. PU 2: 25kW/m^2 for 120 minutes

Time-lapse of the charring process every 30 minutes and the time of the re-ignition.

PU 2 - 25 kW/m^2 - 0:00 min.

PU 2 - 25 kW/m^2 - 30:00 min.

PU 1 - 25 kW/m^2 - 60:00 min.

PU 2 - 25 kW/m^2 - 84:00 min.

PU 2 - 25 kW/m^2 - 90:00 min.

PU 2 - 25 kW/m^2 - 120:00 min.

Figure 43. Time-lapse PU 2. 25 kW/m^2 for 120 min. Re-ignition at minute 88.

The second PU specimen presented an intense flaming combustion after the initial ignition, decaying after 10 minutes. As the first specimen, horizontal cracks following the wood grain appeared in the front of the sample, a bit later at minute 12. The remaining flames were allocated in small vertical cracks that appeared at minute 14.

A smouldering phase was reached at minute 22. First lamella complete visual charring occurred at minute 76, maintaining a constant smouldering combustion. The re-ignition of the sample with visible flames occurred at minute 88, followed by the first lamella complete fall-off that took place at minute 90.

A constant flaming combustion continued until minute 98. From minute 100 to minute 116 there was a considerable increase in the flame intensity of the combustion. After a short fading period, a second smouldering combustion was reached in the front of the CLT specimen at minute 118.

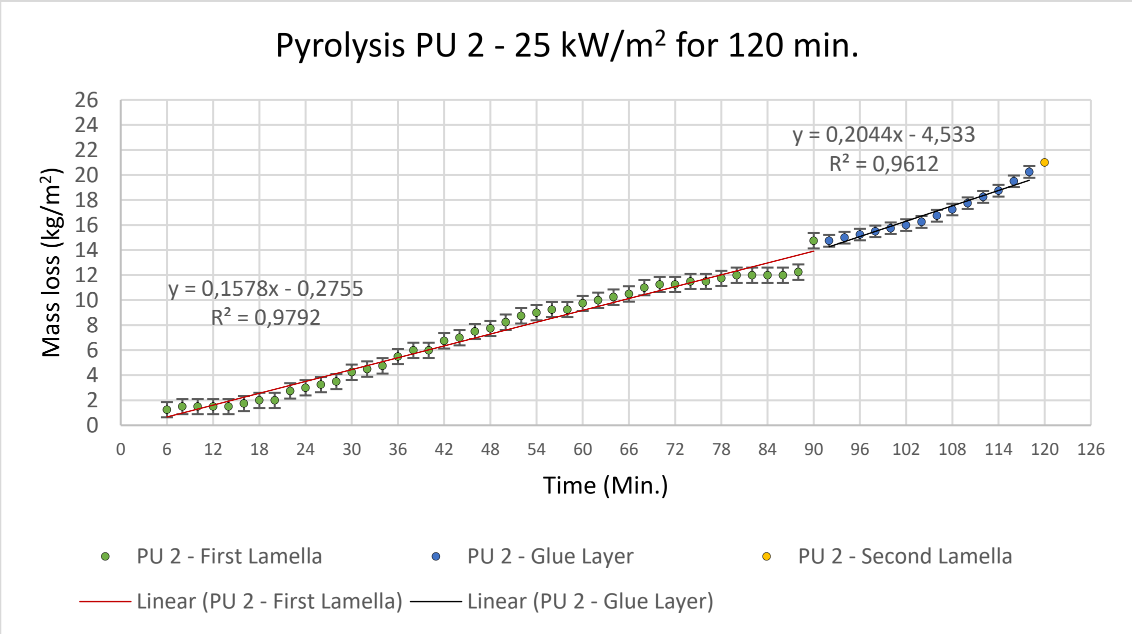


Figure 44. Mass loss per unit surface area graph for specimen PU 2.

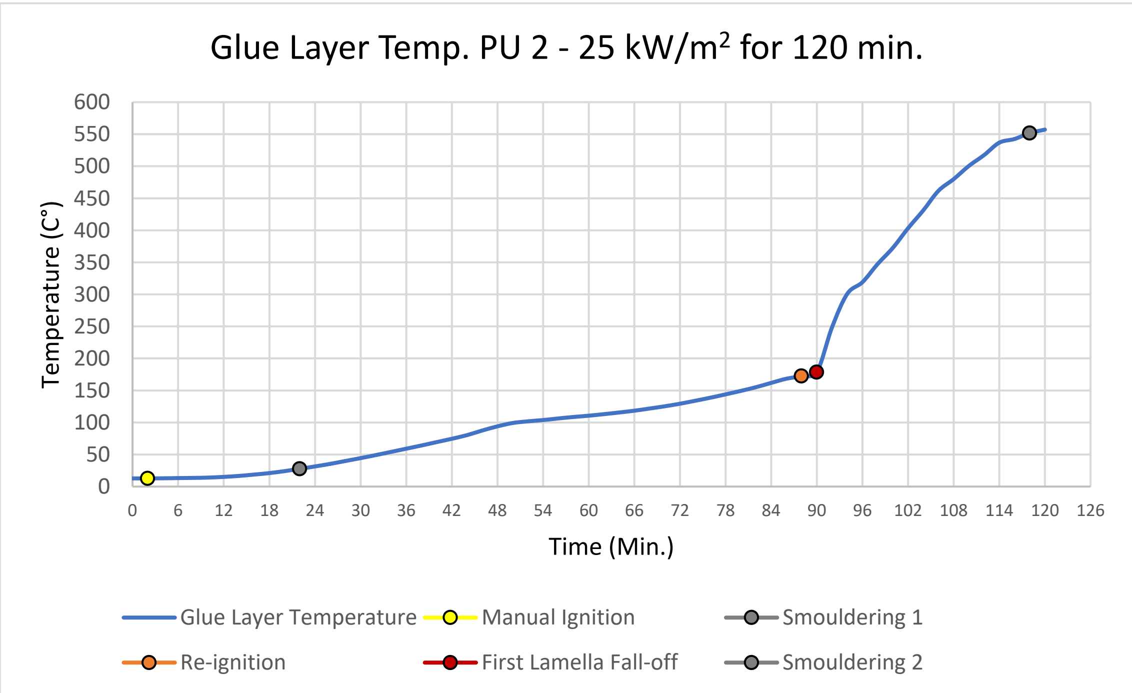


Figure 45. Glue layer temperature graph for specimen PU 2.

Polyurethane adhesive CLT specimen number two (PU 2), presented a prolonged moderate mass loss rate right up to minute 88. At this moment, the re-ignition of timber took place and a considerable mass loss was recorded due to the fist lamella fall-off at minute 90. In this test, the ignition of the complete PU glue layer was set to be exactly at minute 90, increasing from 178 °C to 248 °C in just two minutes. Compared to the first PU specimen, the temperature in the glue layer continued to increased, peaking at 557 °C right in the end of the test. Although the complete glue layer was visible ignited and then surpassed, based on the fact that a second smouldering phase was reached, the thermocouple did not display a sudden decrease of temperature, showing that the sensor was placed slightly behind the glue layer.

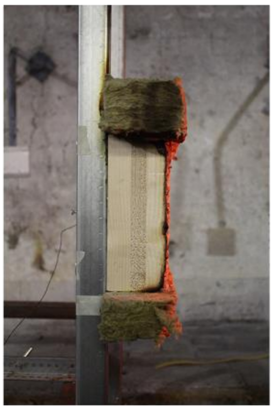
6.2. ME Delamination Control Specimens

First series of experiments. In order to investigate the delamination process on the CLT samples made with ME (Melamine) adhesive, these series used a constant radiation flux for two hours.

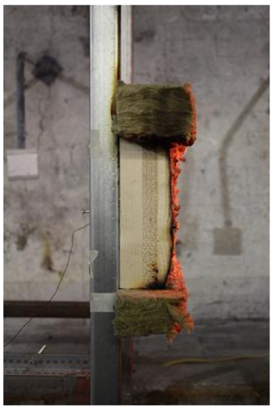
6.2.1. ME 1: 25kW/m^2 for 120 minutes

Time-lapse of the charring process every 30 minutes and the time of the re-ignition.

ME 1 - 25 kW/m^2 - 0:00 min.



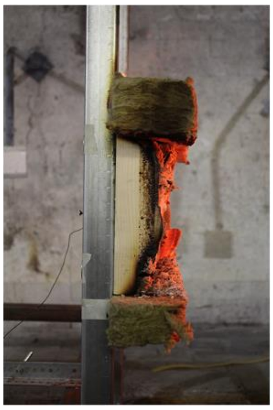
ME 1 - 25 kW/m^2 - 30:00 min.



ME 1 - 25 kW/m^2 - 60:00 min.

ME 1 - 25 kW/m^2 - 66:00 min.

ME 1 - 25 kW/m^2 - 90:00 min.



ME 1 - 25 kW/m^2 - 120:00 min.

Figure 46. Time-lapse ME 1. 25 kW/m^2 for 120 min. Re-ignition at 66 minutes.

The specimen showed and intense flaming combustions after the initial ignition, decaying after 10 minutes. Horizontal and vertical cracks following the wood grain, appeared in the front of the sample at minute 16. The remaining flames lodged in the described cracks and continued to fade until a smouldering phase was reached at minute 30.

A small re-ignition, based on the appearance of small flames took place at minute 44. This continued up to minute 66 in which a bigger re-ignition showed bigger flames. The first lamella complete visual charring occurred at minute 76. A constant and intense flaming combustion was maintained to minute 110, when the first lamella complete fall-off occurred. No additional smouldering combustion was reached before the end of the test.

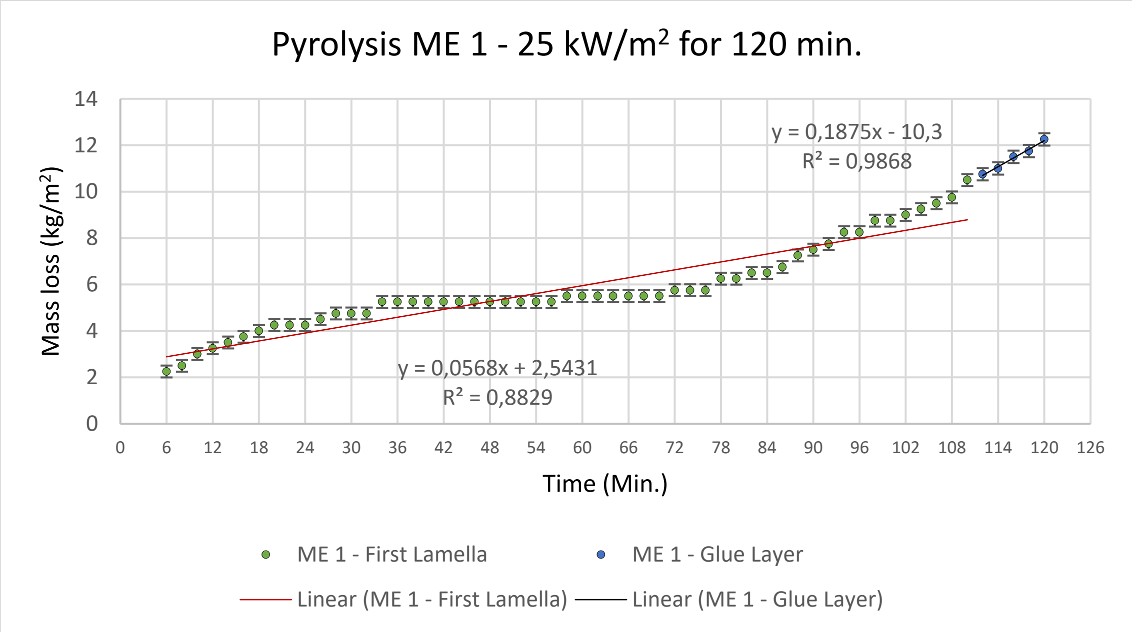


Figure 47. Mass loss per unit surface area graph for specimen ME 1.

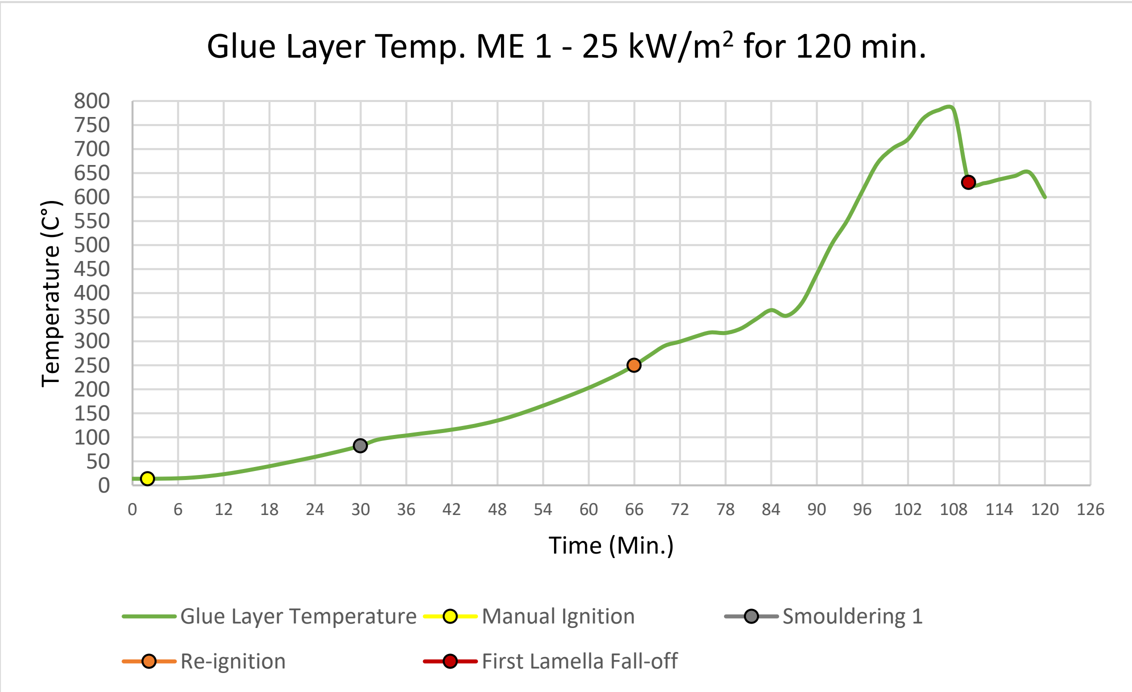


Figure 48. Glue layer temperature graph for specimen ME 1.

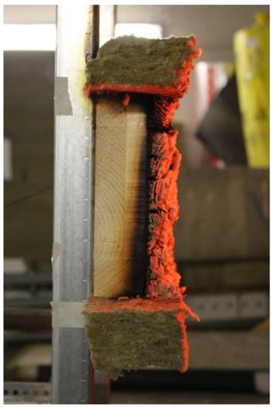
Melamine adhesive CLT specimen number one (ME 1), presented a considerably lower mass loss rate, compared to the PU specimens. Although ME specimen had less mass due to the lamella thickness difference, their performance seemed to be better. First lamella fall-off took place at minute 1100; apparently did not affect the mass loss rate as it continued in a stable way until the end of the test. A relatively constant glue layer temperature increase was shown starting at minute 44, with very small flames that become considerable flames at minute 66. This flaming combustion occurred even before the first lamella complete visual charring, and continued to the end of the test. As in test PU 1, a temperature decrease occurred after glue layer ignition.

6.2.2. ME 2: 25kW/m^2 for 120 minutes

Time-lapse of the charring process every 30 minutes and the time of the re-ignition.

ME 2 - 25 kW/m² - 0:00 min.

ME 2 - 25 kW/m² - 30:00 min.



ME 2 - 25 kW/m² - 60:00 min.

ME 2 - 25 kW/m² - 72:00 min.

ME 2 - 25 kW/m² - 90:00 min.

ME 2 - 25 kW/m² - 120:00 min.

Figure 49. Time-lapse ME 2. 25 kW/m^2 for 120 min. Re-ignition at 70 minutes.

The second ME specimen showed and intense flaming combustions after the initial ignition, decaying after 8 minutes. Vertical cracks following the wood grain, appeared in the front of the sample at minute 12. As in previous tests, the remaining flames lodged in the vertical cracks and continued to fade until a smouldering phase was reached at minute 18, the fastest recorded.

A constant smouldering combustion, was maintained for up to 50 minutes. A constant smoke rate was visible. At minute 62, some cracking noise occurred, indicating a possible fall-off of the first lamella. It was only up to minute 70, when re-ignition took place.

A smaller flaming combustion, compared to specimen ME 1, was maintained until minute 110, when the first lamella complete fall-off occurred. Differently from the initial ME specimen, at minute 118 a smouldering combustion was reached again until the end of the test.

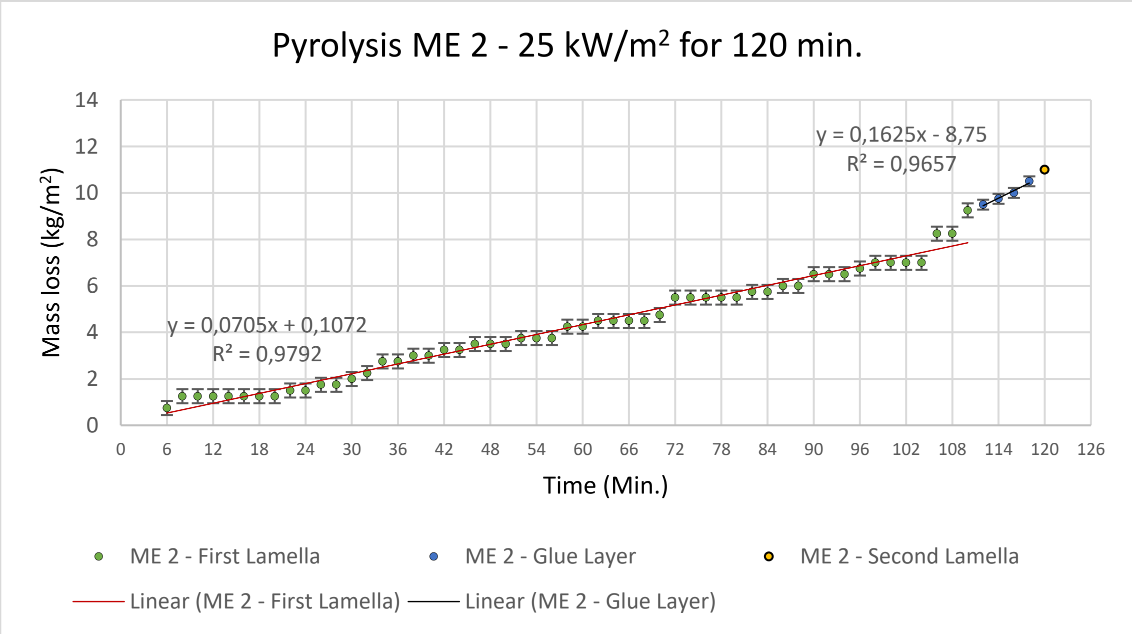


Figure 50. Mass loss per unit surface area graph for specimen ME 2.

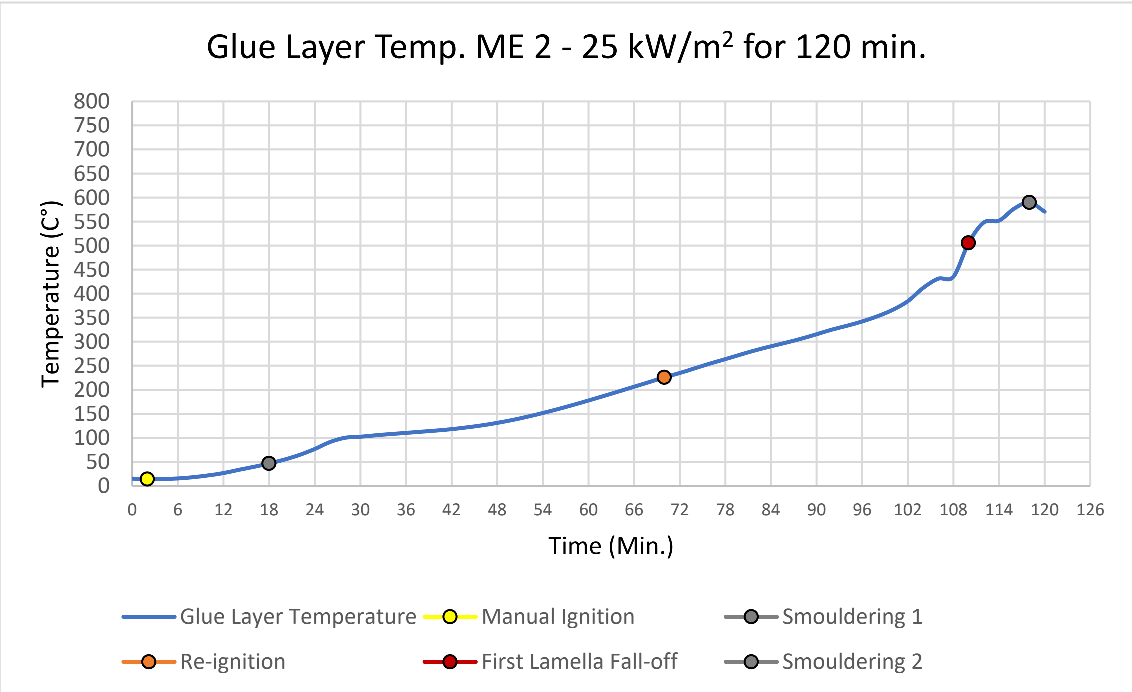


Figure 51. Glue layer temperature graph for specimen ME 2.

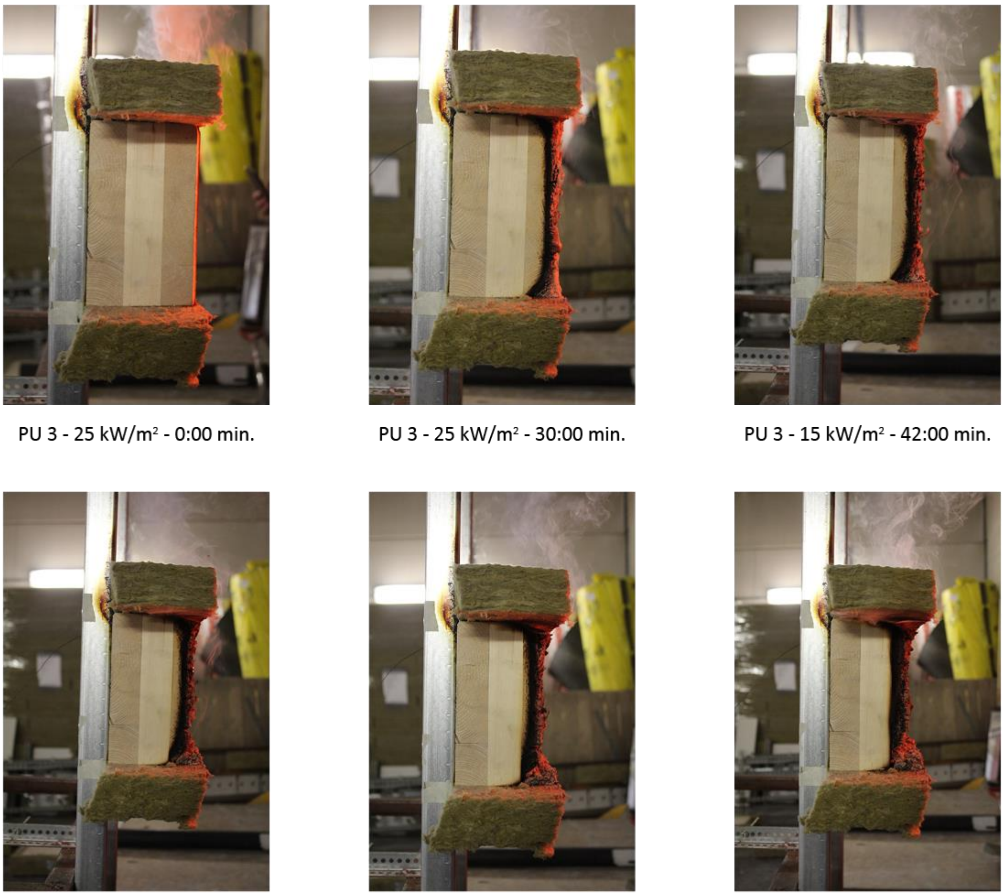
Melamine adhesive CLT specimen number two (ME 2), presented an equally lower mass loss rate, compared to the PU specimens. Once again, ME adhesive seemed to have a better performance, holding its first lamella fall-off took until minute 110. As in specimen ME 1, apparently the lamella fall-off did not affect the mass loss rate as it continued in a stable way increasing slightly in the last two minutes before of the end of the test. A relatively constant glue layer temperature increase started at minute 42, still through a smouldering phase, compared to specimen ME 1. The highest glue layer temperature was reached two minutes before the complete lamella fall-off, indicating that just a small portion of the glue layer was burning before.

6.3. PU at different (Rfx)

Second series of experiments. In order to investigate the self-extinguishment of CLT samples made with PU (Polyurethane) adhesive, these series used a shifting radiation flux in 90 minutes.

6.3.1. PU 3: 25kW/m^2 to 15 kW/m^2

Time-lapse of the charring process every 30 minutes plus charring after the radiation flux shift.



PU 3 - 25 kW/m^2 - 0:00 min. | PU 3 - 25 kW/m^2 - 30:00 min. | PU 3 - 15 kW/m^2 - 42:00 min.

PU 3 - 15 kW/m^2 - 60:00 min. | PU 3 - 15 kW/m^2 - 72:00 min. | PU 3 - 15 kW/m^2 - 90:00 min.

Figure 52. Time-lapse PU 3. 25 kW/m^2 for 30 min. Shift to 15 kW/m^2 for 60 min.

As the initial conditions for the second series of experiments, were the same as in the first series, the behaviour of specimen PU 3 was practically the same up to minute 30. The specimen had an intense flaming combustion after the initial ignition, decaying after 8 minutes. Vertical cracks, following the wood grain appeared in the front of the sample at minute 10. The remaining flames lodged in the described cracks and continued to fade until a smouldering phase was reached at minute 28. First lamella complete visual charring occurred at minute 86.

No re-ignition nor first lamella complete fall-off occurred during the complete duration of the test. A constant smouldering combustion was maintained during the whole test, varying in the smoke rate. A considerable increase in the smoke release rate took place at minute 52, decaying to a slow and constant rate at minute 66. After that, the smoke rate remained steady stable.

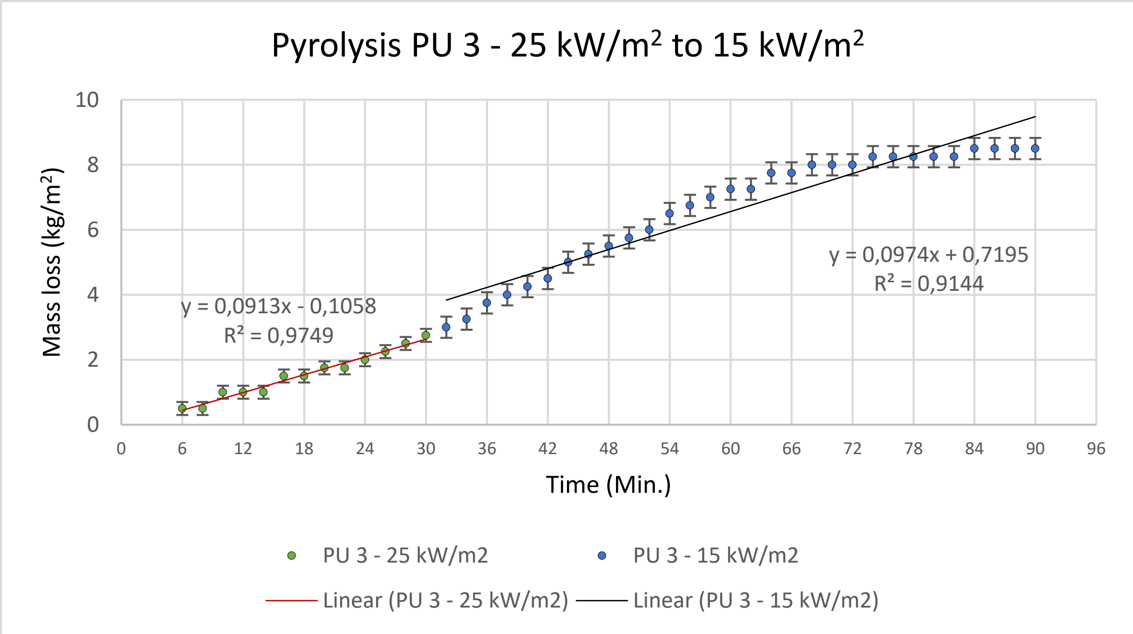


Figure 53. Mass loss per unit surface area graph for specimen PU 3.

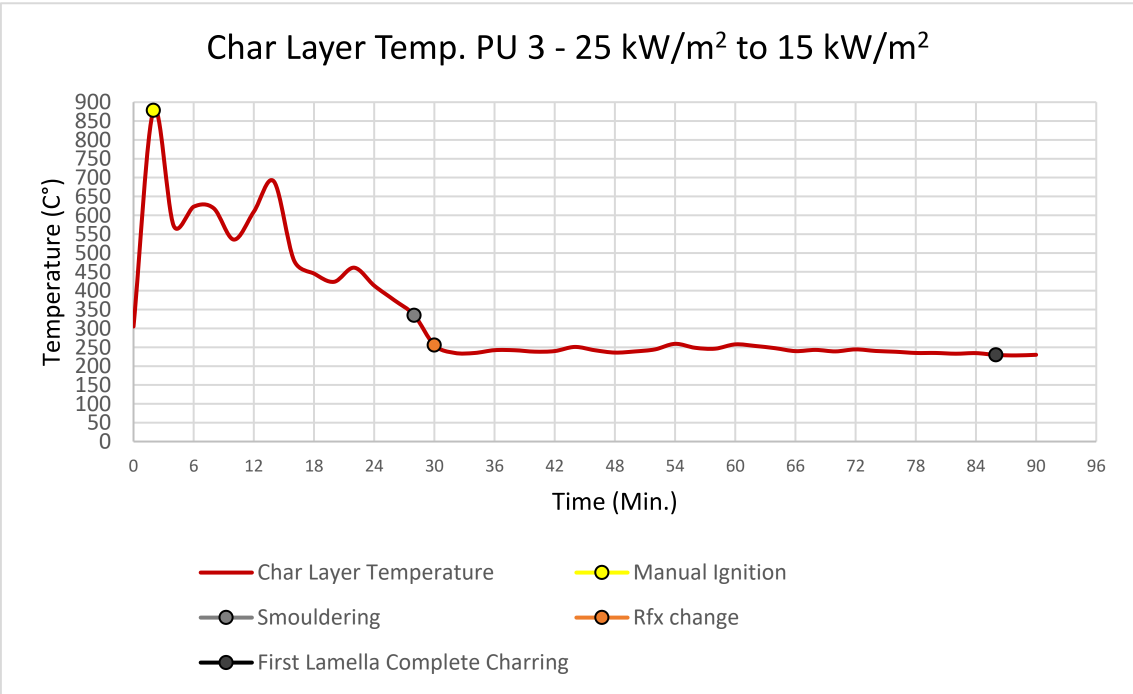


Figure 54. Char layer temperature (front) graph for specimen PU 3.

Polyurethane adhesive CLT specimen number three (PU 3), displayed a complete first lamella charring process, becoming the first one to do it in the second series of experiments. Despite the complete charring, no re-ignition occurred and the specimen stayed in a constant smouldering phase throughout the complete experiment. An edged delamination process took place around minute 58 with no further consequences, understood as fall-off of small portions of char right in the top and bottom edges. The front charring layer temperature started to decrease even before reaching smouldering phase. The front temperature acquired a relative stable value after the radiation flux change, averaging 241 °C for the next 60 minutes.

6.3.2. PU 4: 25 kW/m^2 to 10 kW/m^2

Time-lapse of the charring process every 30 minutes plus charring after the radiation flux shift.

PU 4 - 25 kW/m^2 - 0:00 min.

PU 4 - 25 kW/m^2 - 30:00 min.

PU 4 - 10 kW/m^2 - 42:00 min.

PU 4 - 10 kW/m^2 - 60:00 min.

PU 4 - 10 kW/m^2 - 72:00 min.

PU 4 - 10 kW/m^2 - 90:00 min.

Figure 55. Time-lapse PU 4. 25 kW/m^2 for 30 min. Shift to 10 kW/m^2 for 60 min.

The behaviour of specimen PU 4 was similar to the previous PU test up to minute 30 when the radiation heat flux change took place. The specimen had an intense flaming combustion after the initial ignition, decaying after 10 minutes. Horizontal and vertical cracks, following the wood grain appeared in the front of the sample at minute 12.

The remaining flames lodged in the bottom of the cracks and continued to fade until a smouldering phase was reached at minute 26. The specimen displayed a very slow charring process, compared to the PU 3 test, at the point that there was not a complete first lamella complete charring, only around a 37% of the first lamella got charred. No re-ignition took place during the experiment and the specimen maintained a constant smouldering combustion up to the end of the test. A very small smoke rate was present up to minute 44, after that time a slightly increase of the smoke rate was visible and was maintained until the ended of the test.

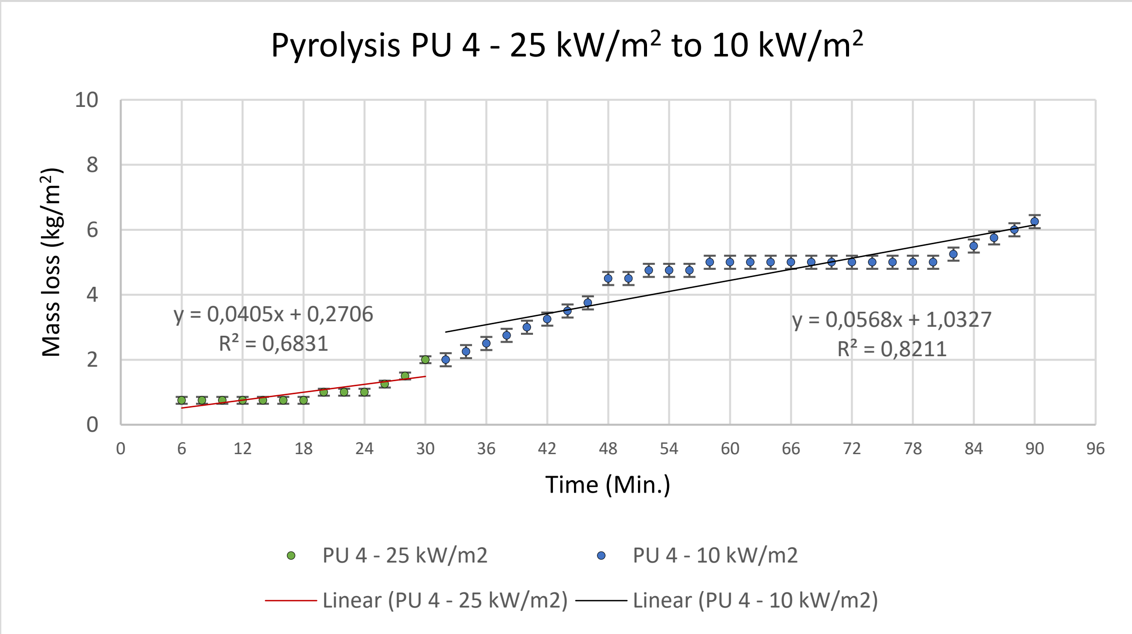


Figure 56. Mass loss per unit surface area graph for specimen PU 4.

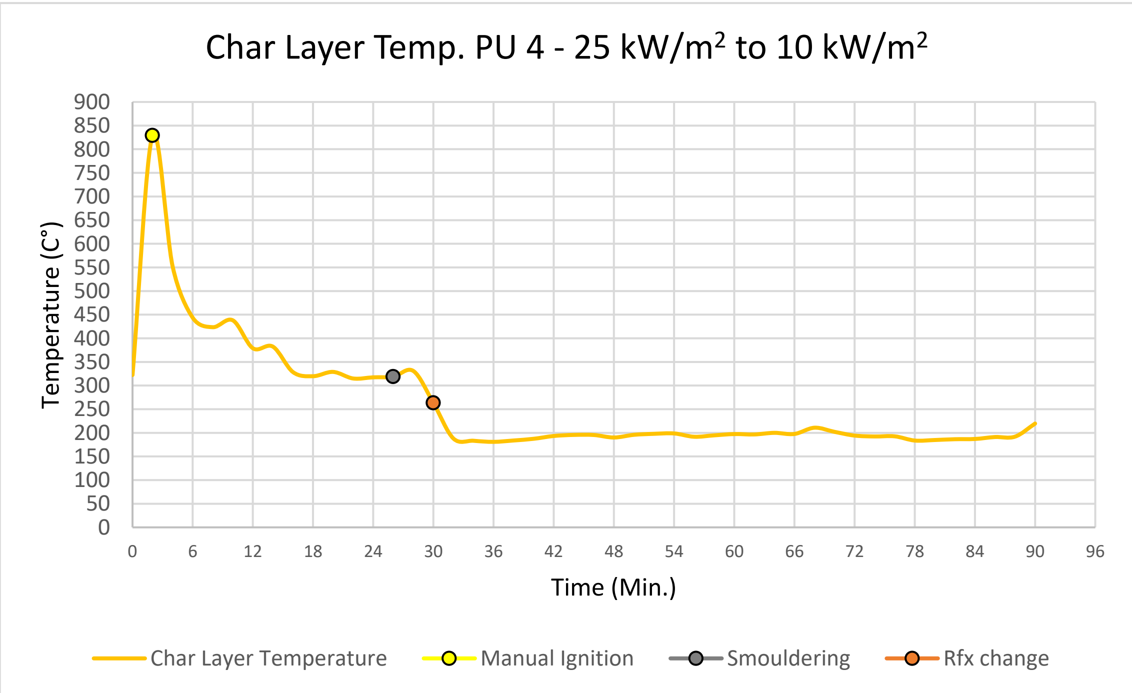


Figure 57. Char layer temperature (front) graph for specimen PU 4.

Polyurethane adhesive CLT specimen number four (PU 4), showed a slower charring process compared to specimen PU 3. No complete first lamella charring nor re-ignition occurred and the specimen stayed in a constant smouldering phase throughout the complete experiment. An edged delamination process took place around minute 56, displaying a fall-off of small portions of char right in the top and bottom edges. The front charring layer temperature started to decrease even before reaching smouldering phase. The front temperature acquired a relative stable value after the radiation heat flux change, averaging 195 °C for the next 60 minutes.

6.3.3. PU 5: 25 kW/m^2 to 5 kW/m^2

Time-lapse of the charring process every 30 minutes plus charring after the radiation flux shift.

PU 5 - 25 kW/m^2 - 0:00 min.

PU 5 - 25 kW/m^2 - 30:00 min.

PU 5 - 5 kW/m^2 - 42:00 min.

PU 5 - 5 kW/m^2 - 60:00 min.

PU 5 - 5 kW/m^2 - 72:00 min.

PU 5 - 5 kW/m^2 - 90:00 min.

Figure 58. Time-lapse PU 5. 25 kW/m^2 for 30 min. Shift to 5 kW/m^2 for 60 min.

Specimen PU 5 behaved practically the same as the previous PU tests. Vertical cracks, following the wood grain appeared in the front of the sample at minute 6. The specimen had an intense flaming combustion after the initial ignition, decaying after 10 minutes. The remaining flames seemed very pale, compared to the previous PU tests and also lodged in the bottom of the cracks and continued to fade until a smouldering phase was reached at minute 28.

As specimen PU 4, PU 5 displayed an even slower charring process, compared to the PU 3 test, also avoiding a complete first lamella complete charring. Around a 20% of the first lamella got charred. A decaying smoke rate was present up to minute 52, after that time a slightly increase of the smoke rate in the right side of the specimen was visible and was maintained until the ended of the test. No re-ignition took place during the experiment and the specimen maintained a constant smouldering combustion up to the end of the test, as the previous PU specimens.

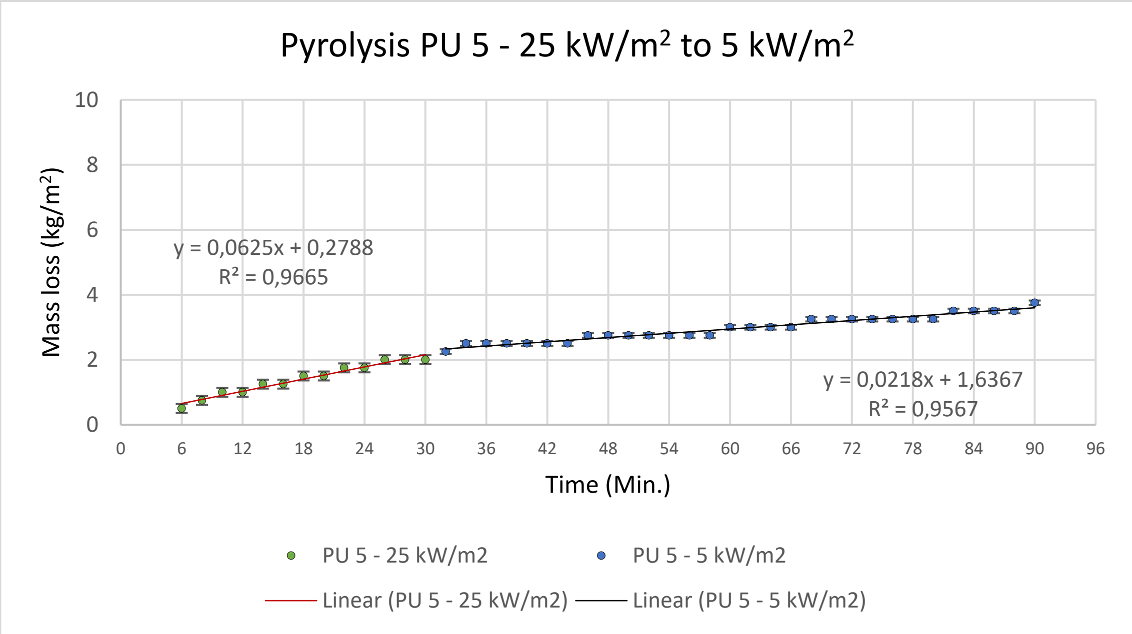


Figure 59. Mass loss per unit surface area graph for specimen PU 5.

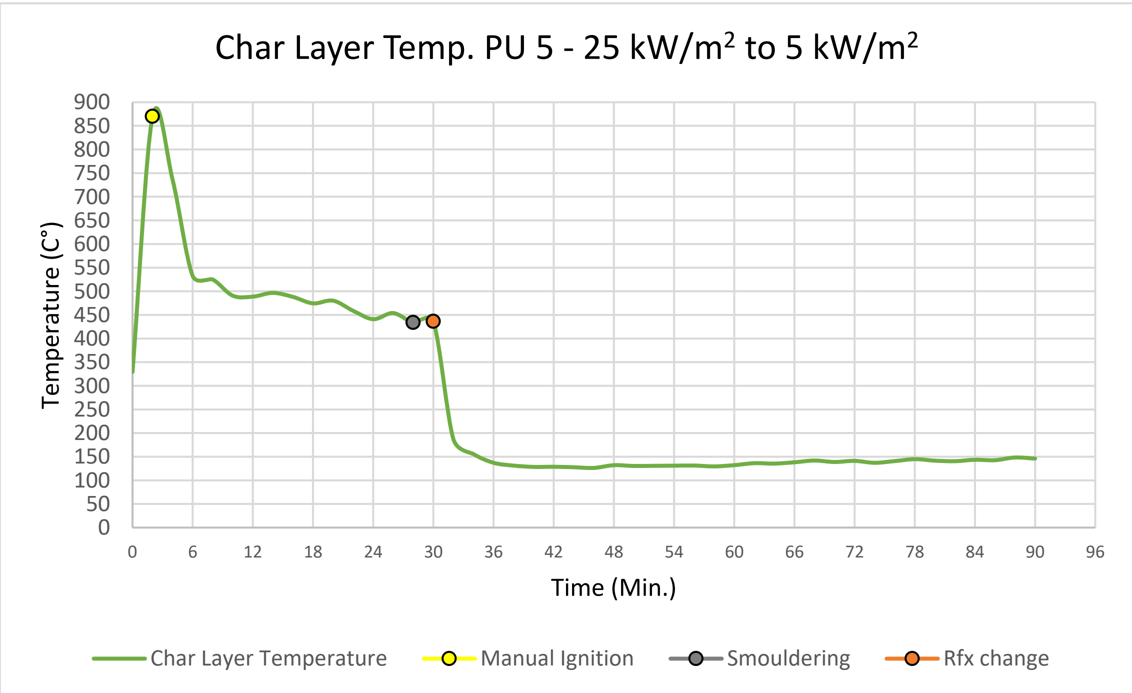


Figure 60. Char layer temperature (front) graph for specimen PU 5.

Polyurethane adhesive CLT specimen number five (PU 5), displayed an even slower charring process compared to specimen PU 4. An edged delamination process took place around minute 62, showing a fall-off of small portions of char right in the top and bottom edges, way later than in specimen PU 4. No complete first lamella charring nor re-ignition occurred and the specimen stayed in a constant smouldering phase throughout the complete experiment. The front charring layer temperature, also started to decrease even before reaching smouldering phase. The front temperature acquired a relative stable value after the radiation heat flux change, averaging 148 °C for the next 60 minutes until the end of the test.

6.4. ME at different (Rfx)

Second series of experiments. In order to investigate the self-extinguishment of CLT samples made with ME (Melamine) adhesive, these series used a shifting radiation flux in 90 minutes.

6.4.1. ME 3: 25 kW/m^2 to 15 kW/m^2

Time-lapse of the charring process every 30 minutes plus charring after the radiation flux shift.

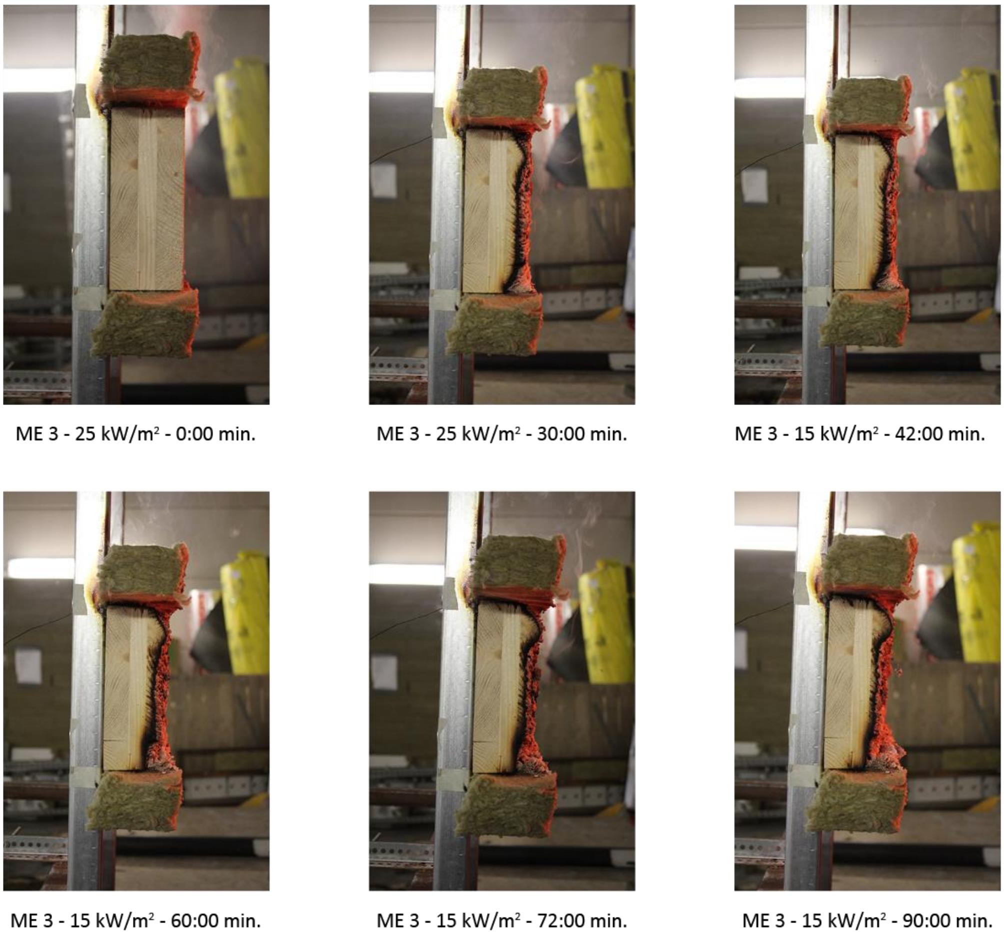


Figure 61. Time-lapse ME 3. 25 kW/m^2 for 30 min. Shift to 15 kW/m^2 for 60 min.

The first ME specimen for the second series of experiments, behaved relatively similar to the previous ME tests up to minute 30. The specimen had an intense flaming combustion after the initial ignition, decaying after 8 minutes. Vertical cracks, following the wood grain appeared in the front of the sample at minute 12. The remaining flames lodged in the bottom of the cracks and continued to fade until a smouldering phase was reached at minute 28. A charring process that consumed at least 73% of the first lamella was visible until minute 63.

No re-ignition nor first lamella complete fall-off occurred during the complete duration of the test. A constant smouldering combustion was maintained during the whole test. A slow smoke rate was present up to minute 42, after that, there was a slightly increase that decreased again at minute 76, after that the smoke rate continued steady stable up to the end of the test.

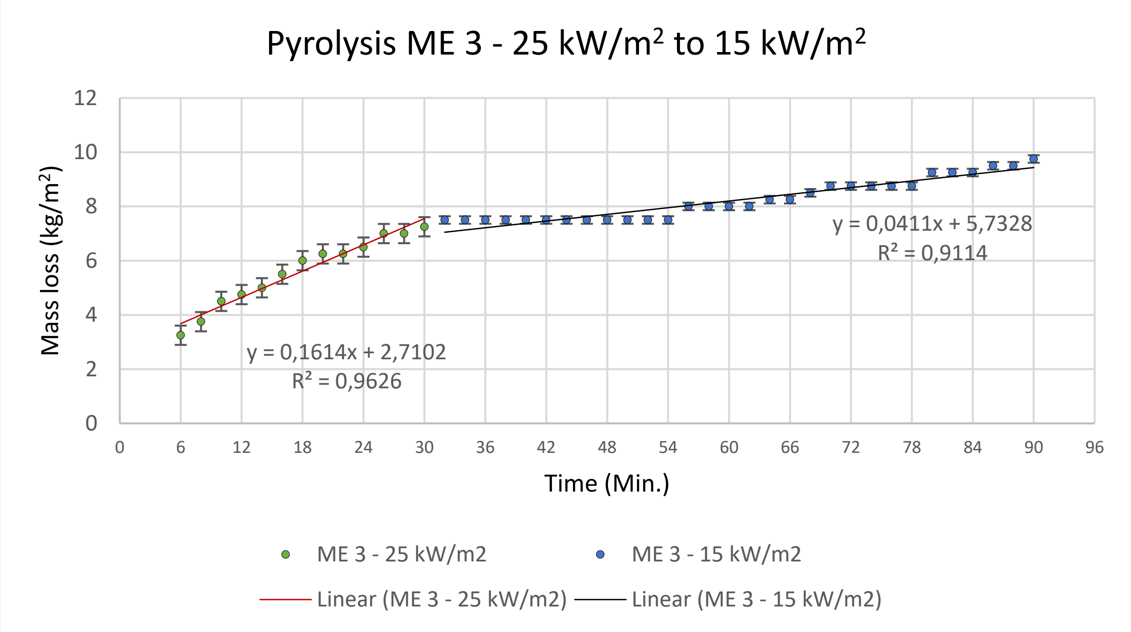


Figure 62. Mass loss per unit surface area graph for specimen ME 3.

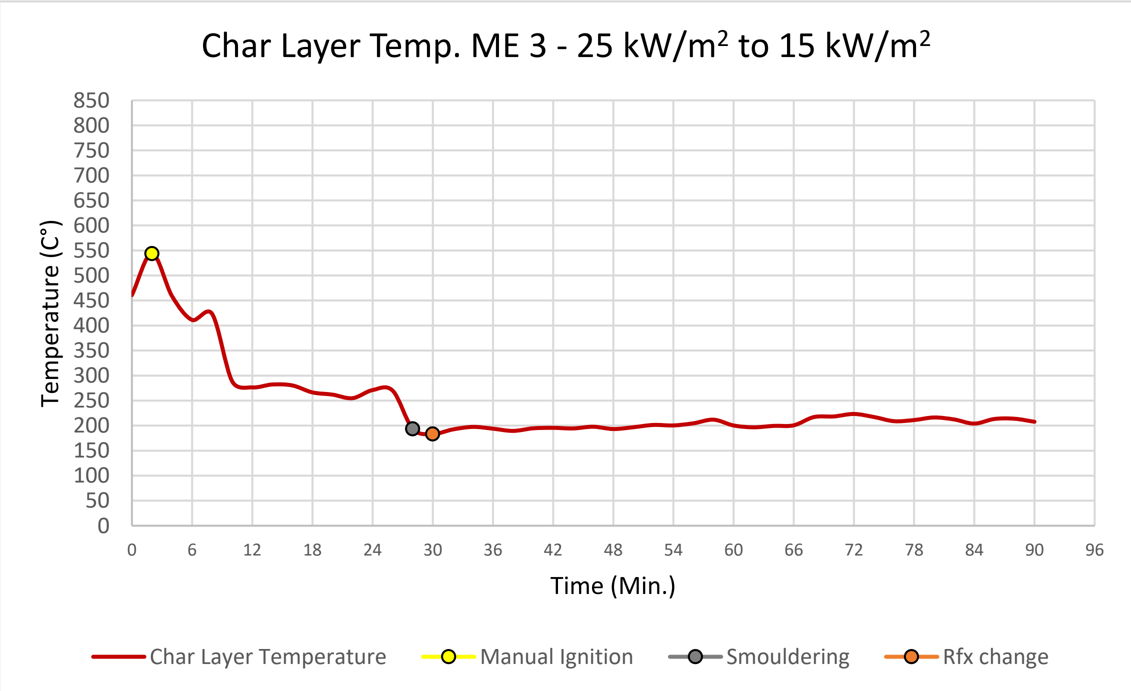


Figure 63. Char layer temperature (front) graph for specimen ME 3.

Melamine adhesive CLT specimen number three (ME 3), displayed an evident lower charring process compared to specimen ME 2. No complete first lamella charring nor re-ignition occurred and the specimen stayed in a constant smouldering phase throughout the complete experiment. An initial weakening of the edged lamella, took place at minute 44. The delamination process took place around minute 56, showing a fall-off of small portions of char right in the top and bottom edges. The front charring layer temperature started to decrease before reaching smouldering phase. The front temperature acquired a relative stable value after the radiation heat flux change, averaging 203 °C for the next 60 minutes until the end of the test.

6.4.1. ME 4: 25 kW/m^2 to 10 kW/m^2

Time-lapse of the charring process every 30 minutes plus charring after the radiation flux shift.

ME 4 - 25 kW/m^2 - 0:00 min.

ME 4 - 25 kW/m^2 - 30:00 min.

ME 4 - 10 kW/m^2 - 42:00 min.

ME 4 - 10 kW/m^2 - 60:00 min.

ME 4 - 10 kW/m^2 - 72:00 min.

ME 4 - 10 kW/m^2 - 90:00 min.

Figure 64. Time-lapse ME 4. 25 kW/m^2 for 30 min. Shift to 10 kW/m^2 for 60 min.

Specimen ME 4 behaved significantly different to the previous ME 3 tests, showing a higher front temperature right after the manual ignition. The specimen had an intense flaming combustion, decaying after 6 minutes. Horizontal and vertical cracks, following the wood grain appeared in the front of the sample at minute 8. The remaining flames lodged in the bottom of the cracks and continued to fade until a smouldering phase was reached at minute 26. A complete charring process of the first lamella was completed at minute 82.

No re-ignition nor first lamella complete fall-off occurred during the complete duration of the test. A constant smouldering combustion was maintained during the whole test, with a slow smoke rate that ended at minute 44. A slightly increase in the smoke rate was recorded at minute 46, which finally continued steady stable up to the end of the test.

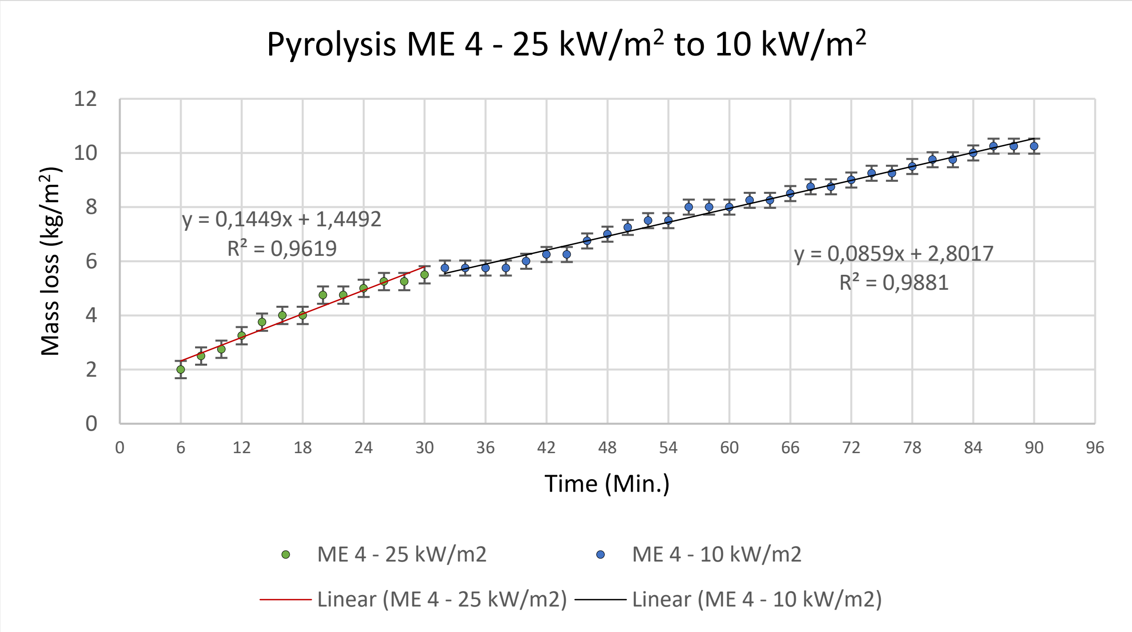


Figure 65. Mass loss per unit surface area graph for specimen ME 4.

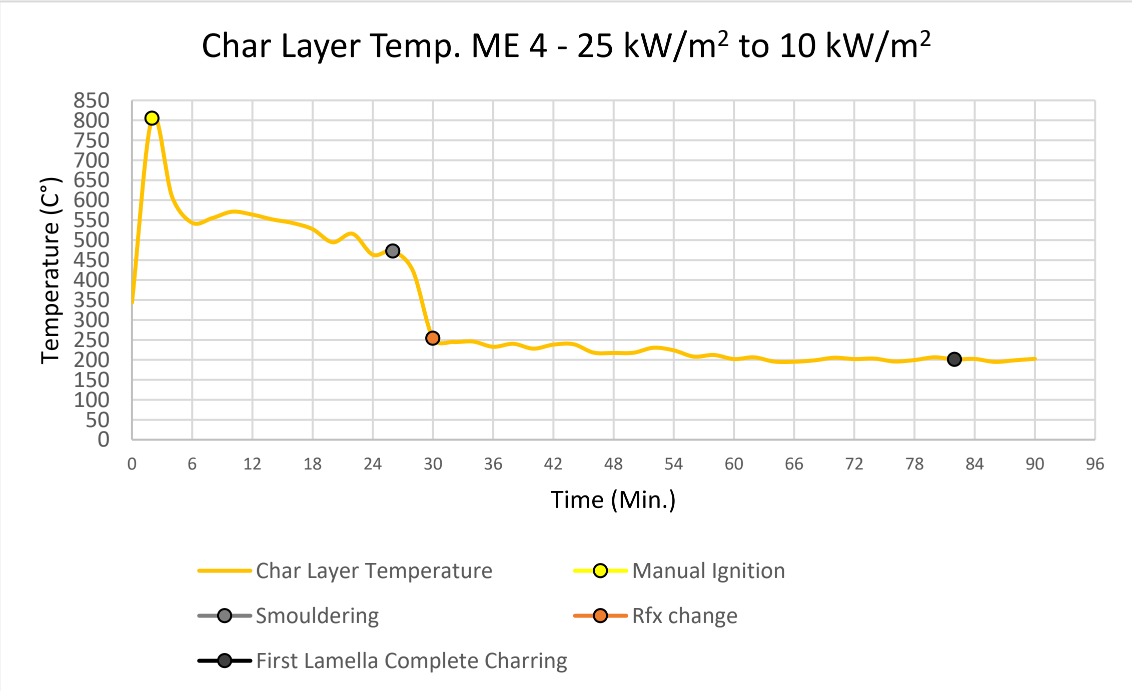


Figure 66. Char layer temperature (front) graph for specimen ME 4.

Melamine adhesive CLT specimen number four (ME 4), displayed a slightly higher charring process compared to specimen ME 3. Despite the complete charring, no re-ignition occurred and the specimen stayed in a constant smouldering phase throughout the complete experiment. The front charring layer temperature also started to decrease before reaching smouldering phase. The front temperature acquired a relative stable value after the radiation heat flux change, averaging 214 °C for the next 60 minutes, showing a slightly higher temperature compared to the previous ME specimen test. Contrary to expectations, specimen ME 4 performed worse at a lower radiation heat flux in almost all the evaluated aspects.

6.4.1. ME 5: 25 kW/m^2 to 5 kW/m^2

Time-lapse of the charring process every 30 minutes plus charring after the radiation flux shift.

ME 5 - 25 kW/m^2 - 0:00 min.

ME 5 - 25 kW/m^2 - 30:00 min.

ME 5 - 5 kW/m^2 - 42:00 min.

ME 5 - 5 kW/m^2 - 60:00 min.

ME 5 - 5 kW/m^2 - 72:00 min.

ME 5 - 5 kW/m^2 - 90:00 min.

Figure 67. Time-lapse ME 5. 25 kW/m^2 for 30 min. Shift to 5 kW/m^2 for 60 min.

The final ME specimen for the second series of experiments, behaved relatively similar to specimen ME 3 up to minute 30. The specimen had an intense flaming combustion after the initial ignition, decaying after 8 minutes. Vertical cracks, following the wood grain appeared in the front of the sample at minute 10. The remaining flames lodged in the bottom right side of the cracks and continued to fade until a smouldering phase was reached at minute 28. A considerable slower charring process compared to the previous ME tests was evident.

No re-ignition nor first lamella complete fall-off occurred during the complete duration of the test. A constant smouldering combustion was maintained during the whole test. A slow smoke rate was present up to minute 36, after that, there was a slightly increase at minute 38. The smoke rate stabilized after that point and continued steady stable up to the end of the test with a little more evidence of smoke release on the right side of the specimen.

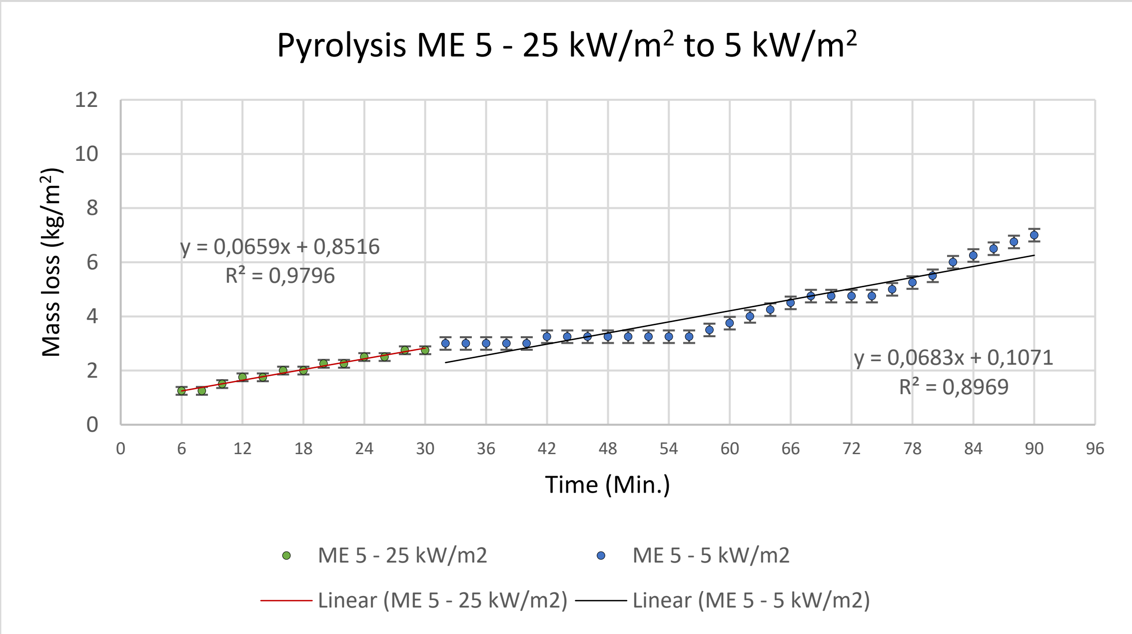


Figure 68. Mass loss per unit surface area graph for specimen ME 5.

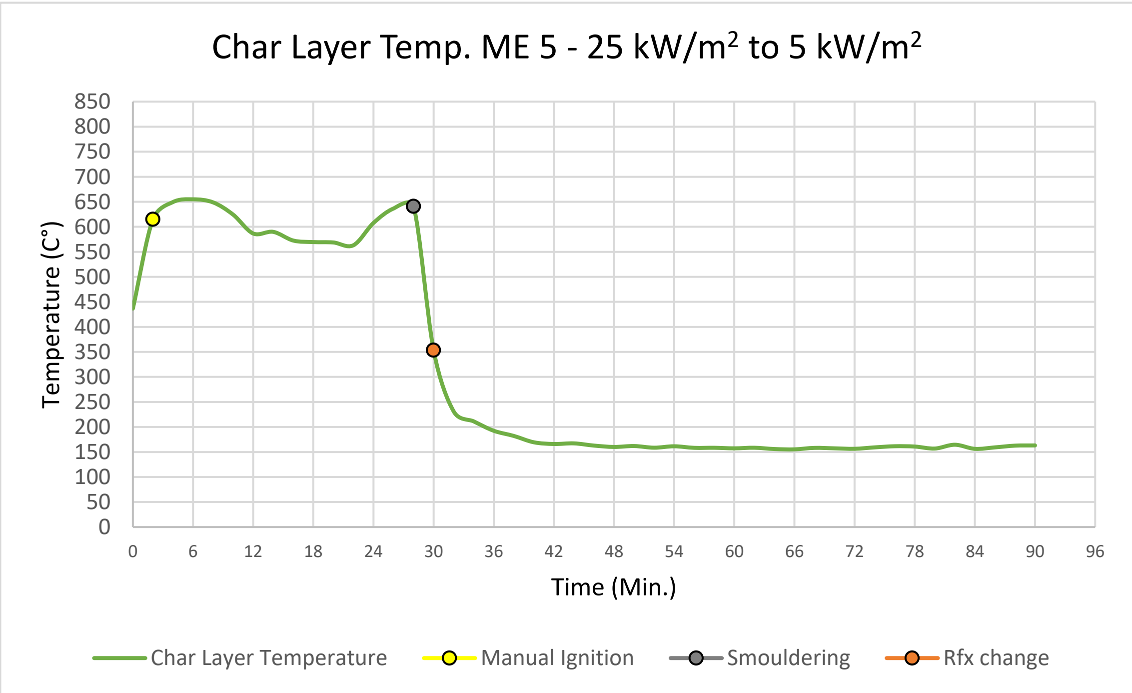


Figure 69. Char layer temperature (front) graph for specimen ME 5.

Melamine adhesive CLT specimen number five (ME 3), displayed an evident lower charring process compared to specimens ME 3 and ME 4. Around minute 58, a fall-off of small portions of char right in the bottom edges occurred. No complete first lamella charring nor re-ignition occurred and the specimen stayed in a constant smouldering phase throughout the complete experiment. Contrary to all previous experiments of the second series, the front charring layer temperature did increase before reaching smouldering phase. After the smouldering, the front temperature started to decrease and acquired a relative stable value, slightly later after the radiation heat flux change, averaging 161 °C for the next 52 minutes until the end of the test.

7. Conclusions

- Smouldering combustion (a slow, flameless form of combustion) was reached by all specimens on average at minute 26. This could indicate that the glue type had no mayor influence within the first 30 minutes of combustion of the CLT samples.

- The influence of the adhesive type was evident only in the first series of experiments, acting as the main reason of the re-ignition of the tested specimens. Glue then, might play a significant role for unprotected CLT exposed to long periods of combustion, as being a trigger mechanism for a new flaming combustion if self-extinguishment does not occur and if there is no external repressive action (fire services).

- Char fall-off displayed to be a fundamental factor in both series of experiments, to prevent a re-ignition scenario and to maintain a constant smouldering combustion that would lead to self-extinguishment with the right compartment conditions.

- An average equal mass loss rate was expected to be present in the initial 30 minutes of all testing specimens, as the initial conditions were the same in both series of experiments. The steep differences between all mass loss per unit surface area graphs, can be translated into a high uncertainty due to the natural material character of timber, used to produce CLT panels. By not having very well-defined properties, understood as different wood grains, internal unknown moisture and variable and randomized cellulose configurations product of the trees' growing conditions, wood variance could be the answer to the uneven initial behaviour of the samples.

- Based on the results of the first series of experiments, Melamine (ME) adhesive samples seemed to have a better performance withstanding a charring process. While the complete first lamella fall-off occurred at minute 90 in both Polyurethane (PU) samples, having a thicker lamella dimension (40 mm), the first lamella fall-off (30 mm) of the ME samples occurred at minute 110. This could indicate a considerable glue influence on the timber configuration, understood as a possible deep impregnation from the side of the PU adhesive, as it possibly penetrated the wood during the production process and thus, accelerated the charring and burning process of the CLT PU samples.

- The front char layer temperature, in the second series of experiments, did not maintain the expected temperature of the initial radiation heat flux of 25 kW/m^2 (550°C) through the first 30 minutes of exposure, even when having an active flaming combustion before reaching the smouldering phase. This might have to be by with a convective cool-down process due to presence of enough ambient air surrounding the specimens, and the radiation character of the heat source; in this way triggering a possible energy balance process between the input radiation and the resulting convection.

- Self-extinguishment was not actually acquired during the experiments. The testing results of the second series of experiments indicated that all samples were still in combustion after the radiation heat flux change and even at the end of the exposure, after 60 minutes.

- However, the temperature decrease shown in Figure X, and the decrease of the mass loss per unit surface area rate shown in Figures X; could indicate early stages of a complete self-extinguishment process, which according to Crielaard et al. (2019), could last longer than 150 minutes with radiation fluxes values below or equal to 6 kW/m^2.

The comparative resulting graphs of both experiments are shown in the following Figures:

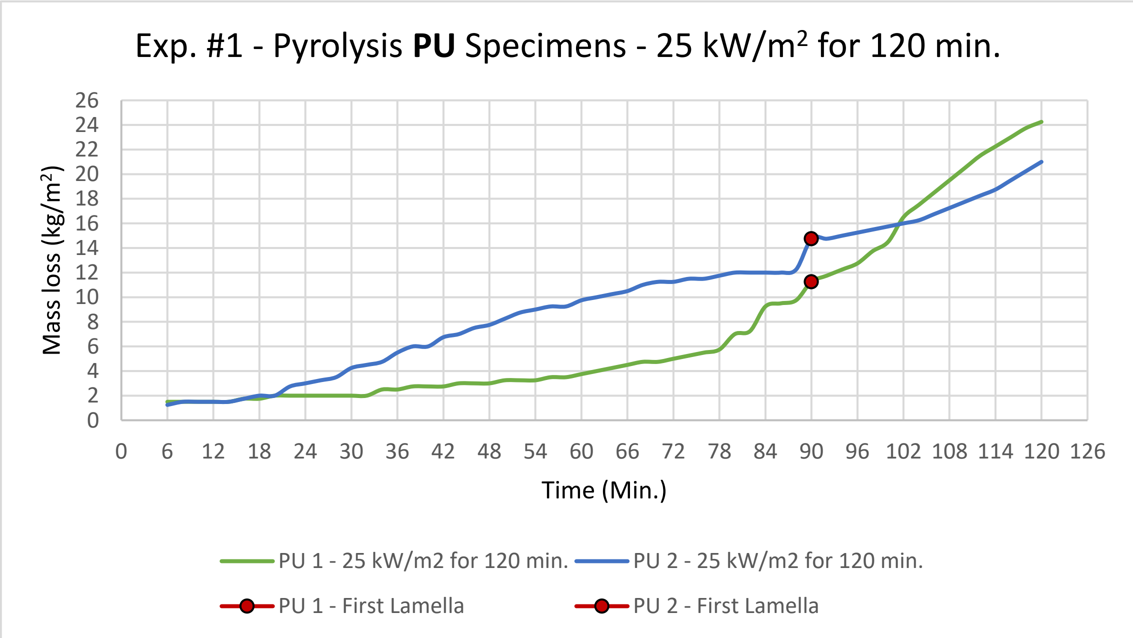


Figure 70. Mass loss per unit surface area comparative graph for PU specimens - Experiments #1.

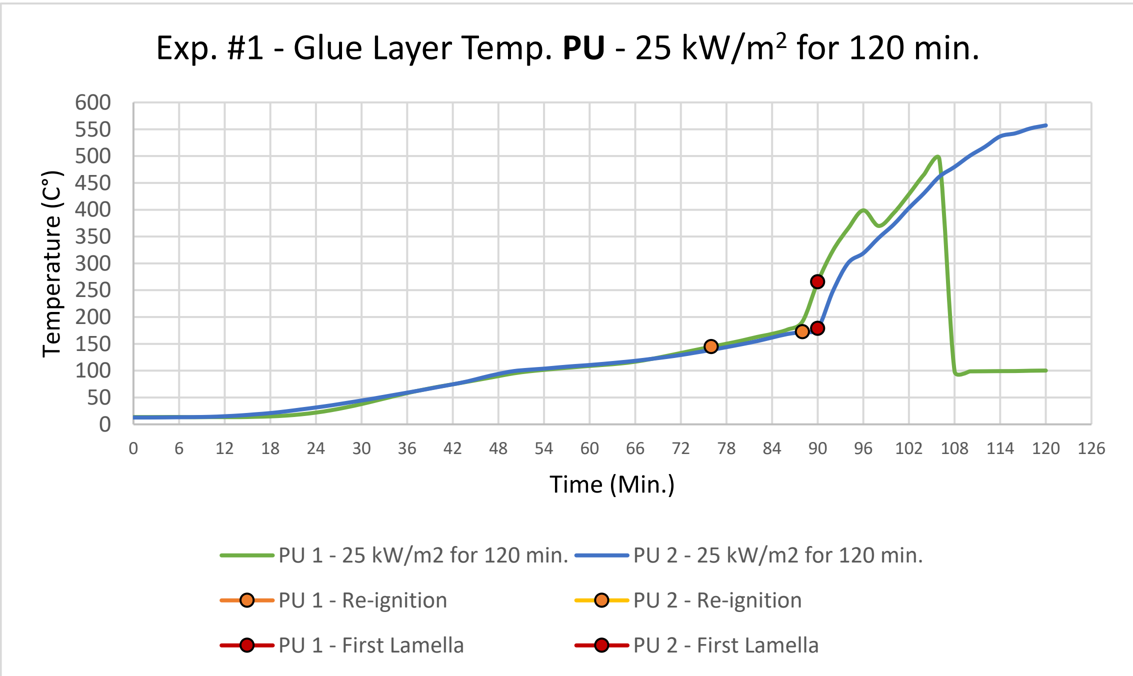


Figure 71. Glue layer temperature comparative graph for PU specimens - Experiments #1.

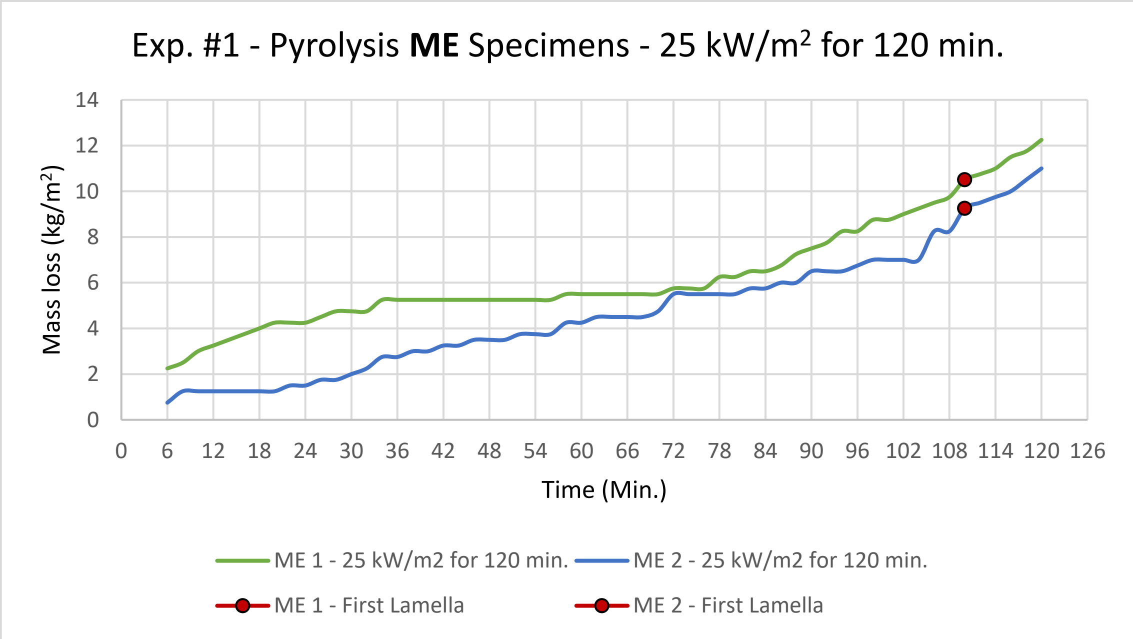


Figure 72. Mass loss per unit surface area comparative graph for ME specimens - Experiments #1.

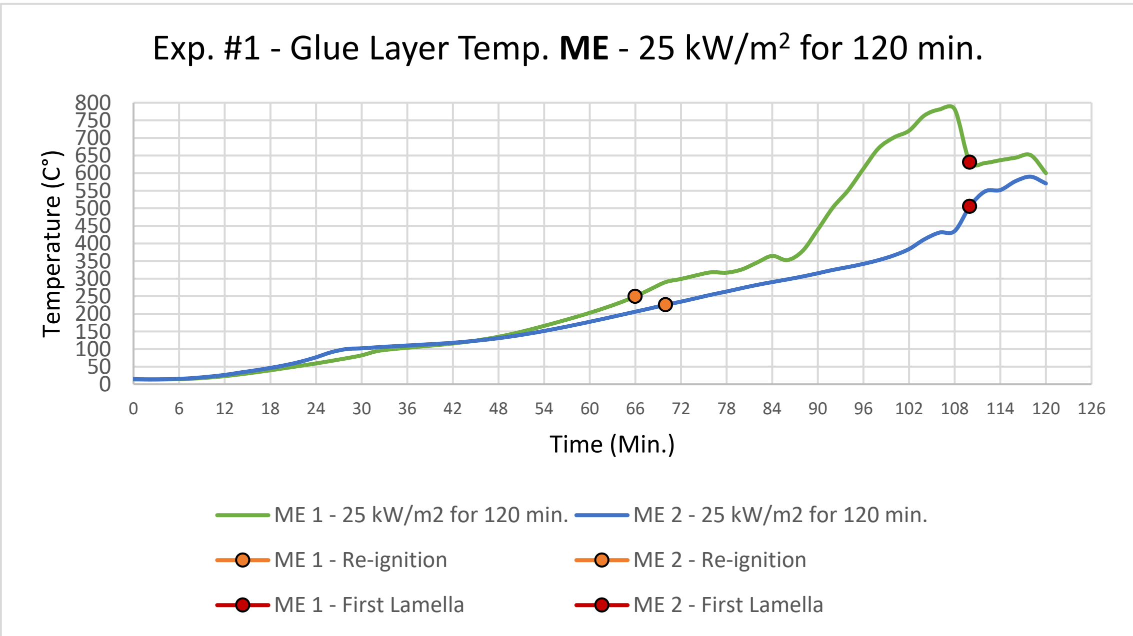


Figure 73. Glue layer temperature comparative graph for ME specimens - Experiments #1.

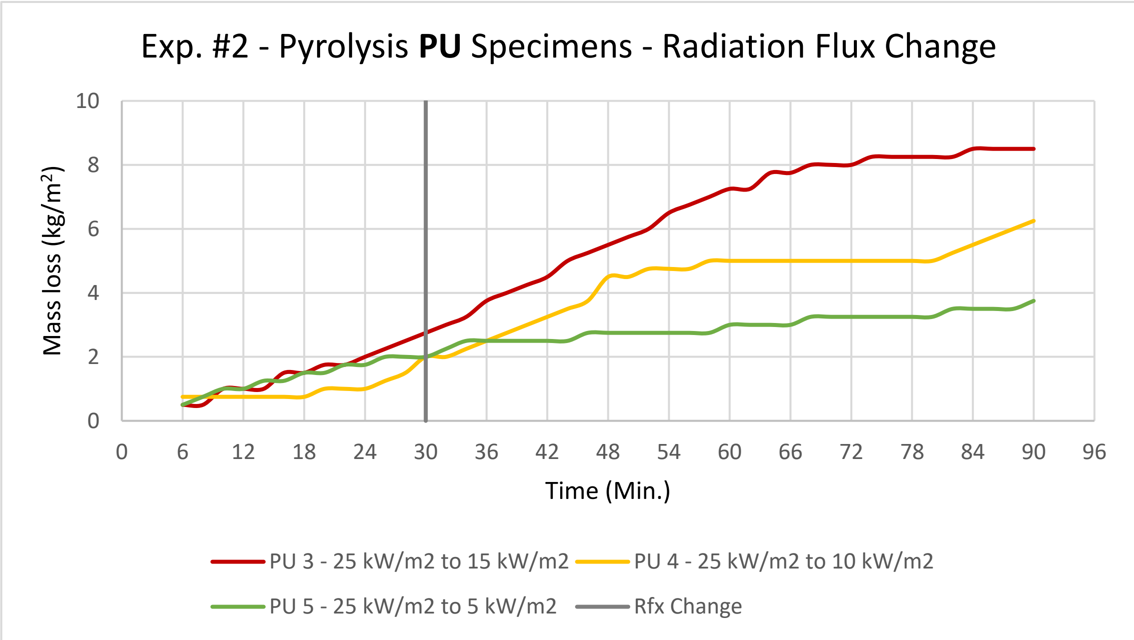


Figure 74. Mass loss per unit surface area comparative graph for PU specimens - Experiments #2.

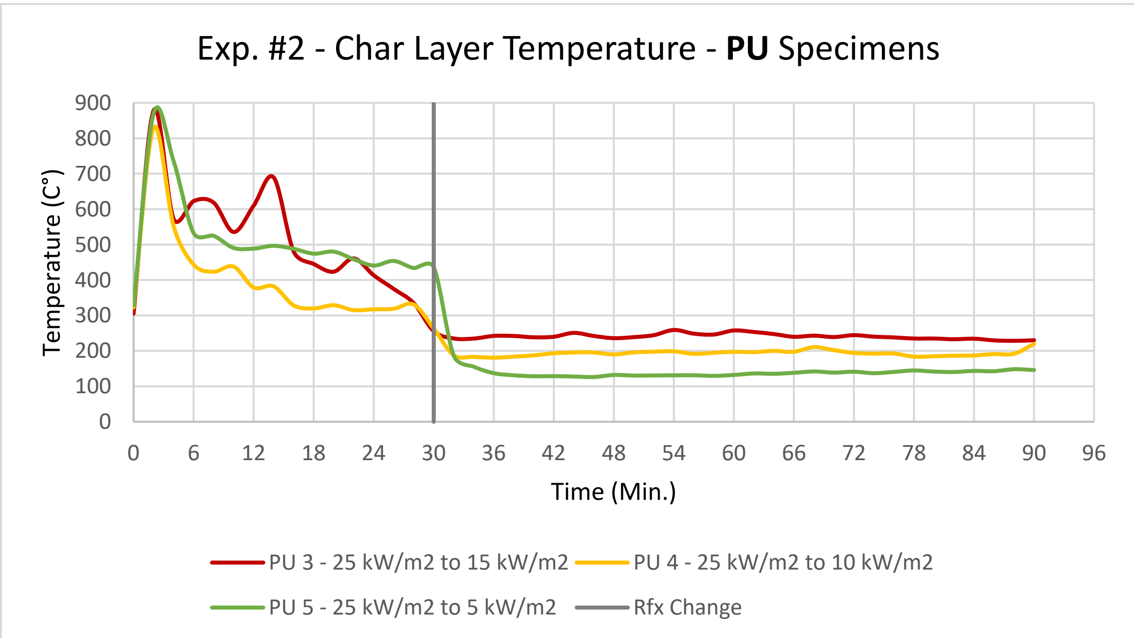


Figure 75. Front char layer temperature comparative graph for PU specimens - Experiments #2.

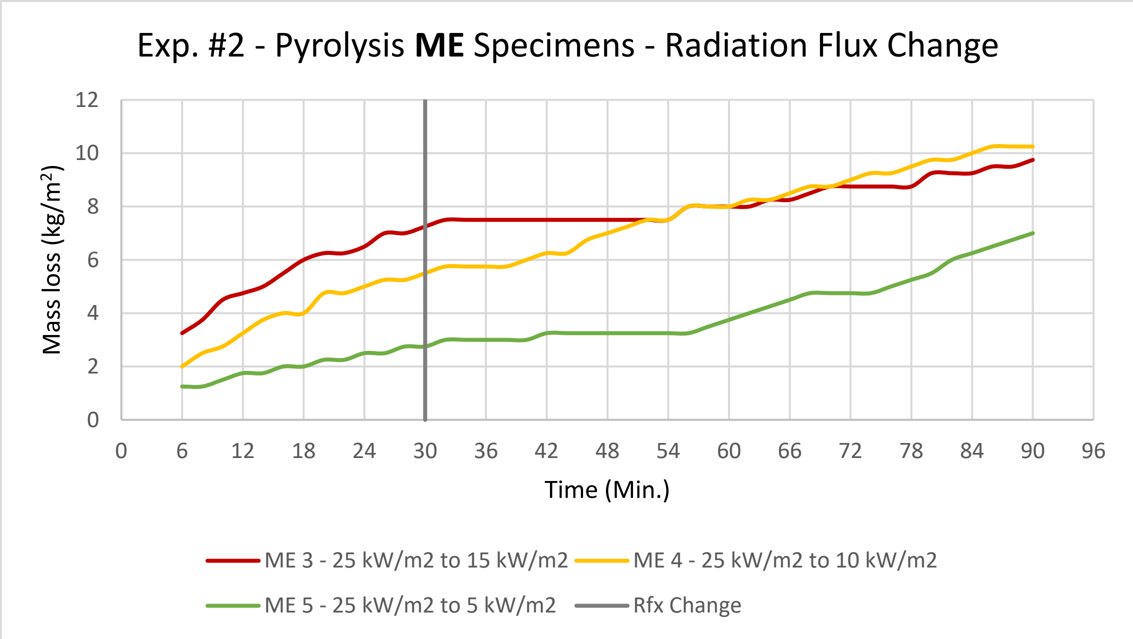


Figure 76. Mass loss per unit surface area comparative graph for ME specimens - Experiments #2.

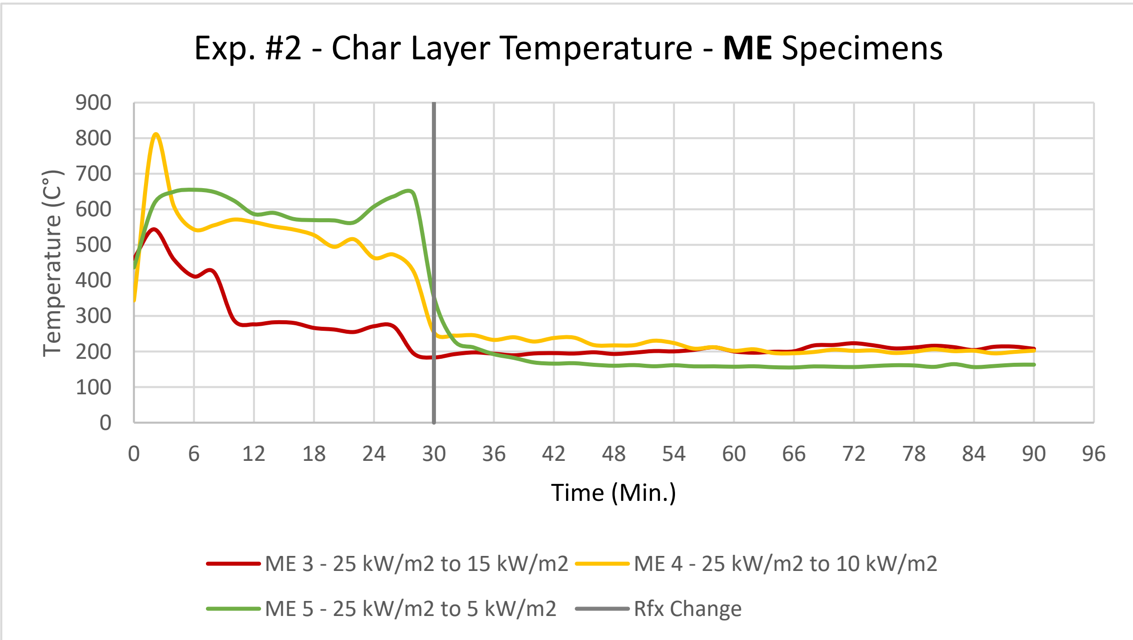


Figure 77. Front char layer temperature comparative graph for ME specimens - Experiments #2.

PART C.
DESIGN INTERPRETATION

PART C. DESIGN INTERPRETATION

1. FSE Performance - Simulation Environment

In order to interpret the obtained data during the laboratory tests, and qualitatively assess the influence of self-extinguishment as property of the material (CLT), inherent to Lines of Defence 1, a fire simulation based on the fire thermal model of natural fire was set to be performed.

The equivalent fire duration (standard fire curve), understood as the calculated time of the compartment total fire without any internal or external mitigation (Van Herpen, 2021), is used as the main tool to investigate the response of an unprotected cross laminated timber compartment (room). Tests' results were used as the boundary conditions for the simulation.

1.1. OZone Simulations

OZone is a software developed to calculate the thermal actions generated by a fire and the evolution of temperature in enclosures, using nominal fire curves or natural fire models based on physical and chemical parameters (Pintea et al., 2018). OZone environment, deals with the two types of natural fire models: localised fires and compartment fires (Pintea et al., 2018).

1.2. Simulation Inputs

Based on the work of Van Herpen, R. (2021), in which a comparison between a traditional concrete apartment and a CLT apartment was done through an equivalent fire duration simulation, the assumptions and boundary conditions for the thesis investigation simulation, were stablished according to the experiments results in terms of mass loss rate data recorded. Van Herpen, R. (2021), served as the core basis to set and collate the compartment simulations.

1.2.1. Experiment #1 – 25 kW/m^2 for 120 minutes

During the first series of experiments, a flaming combustion of timber with a thermal load less than 25 kW/m^2 results in a mass loss of approximately 8 kg/m2 in 60 minutes. With a specific mass of 450 kg/m3 of the CLT specimens (DERIX-groep, 2019), the mass loss rate is 0.133 kg/(m^2.min). The burn depth rate in an ideal stoichiometric combustion, a theoretical combustion with the optimal amount of oxygen and fuel mix that generates the most heat possible (Van Herpen, 2021); without taking into account the char layer would be: 0.3 mm/min.

After 60 minutes:

Theory (conservative): Burn depth = 60 x 0.5 = 30 mm
Experiments Results: Burn depth = 60 x 0.3 = 18 mm (combusted) + 12 mm char layer

1.2.1. Experiment #2 – Half and hour 25 kW/m^2 to reduced Rfx

In the second series of experiments, the prolongated smouldering combustion, as the prevalent combustion throughout the test with a thermal load between 5 – 20 kW/m^2, can be translated into a mass loss of approximately 4 kg/m^2 in 60 minutes. This corresponds to a mass loss rate of 0.067 kg/(m^2.min) and a burn depth rate of 0.15 mm/min.

1.3. CLT Fire Scenario

A slightly advanced cross laminated timber apartment model, based on the previous simulations made by Van Herpen, R. (2021) was introduced to the OZone software. The rate of heat release (RHR) caused by burning CLT constructions (tested cross laminated timber specimens) was uniformly distributed over the floor area (compartment area) and added to the RHR caused by the variable fire load of 250 kW/m^2 of the assumed burning materials inside the room.

To calculate the influence cross laminated timber and its burning process, a spreadsheet with the rate of heat release (RHR) calculations based on the mass loss rate aforementioned, was used to input the new conditions and behaviour of the CLT burnt in the laboratory.

In the input spreadsheet, it was assumed a higher RHR of the CLT construction when the fire load inside the compartment is burning using a thermal load greater than 25 kW/m^2, as the internal burning materials; and a lower RHR of the CLT construction when the fire load inside the compartment is combusted, simulating the smouldering combustion studied in the second series of experiments with a thermal load less than 25 kW/m^2.

The data obtained during the tests was roughly used to make a distinction between flaming combustion (when the fire load inside is also burning) and smouldering combustion (when the fire load inside is burnt). The term “roughly” is used due to the complexity of setting up an accurate simulation based on the experiments results with a considerable large uncertainty.

High uncertainty and some hints of self-extinguishment, as the process was not completely achieved during the experiments, led to set the simulation based in the distinction of flaming combustion and smouldering combustion. Indeed, more conservative values should be used as the mass loss rate according to literature is even greater (Van Herpen, 2021). In order to recognize the value of the experiments and the investigation process, the simulation was set to be performed under the mass loss rate and the rate of heat release (RHR) aforementioned.

The total surface of the CLT compartment, as walls and ceiling, excluding flooring, assuming that the floor does not take part in the fire scenario was set to 172 m^2. Windows (two windows of 1.5 x 4.1 m^2) and the door (2.3 x 1.5 m^2) were also excluded, resulting in a CLT surface of 156 m^2.

The fire scenario in the CLT compartment, was stopped when the total energy released by combustion of cross laminated timber was equal to 500 MJ/m2 (in total: 500 x 70 = 35 GJ), which according to the Dutch Building Code (NEN-5128), is the minimum value that should be taken into account in case of a combustible compartment envelope. That value was also used in the concrete compartment simulation of Van Herpen, R. (2021).

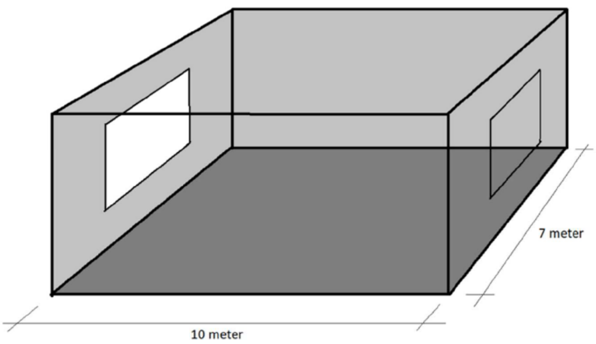


Figure 78. Simulation’s compartment isometry. (Van Herpen, 2021).

1.4. Results

The results of the simulation are displayed as the equivalent fire duration of the fire inside the compartments. As aforementioned, Van Herpen, R. (2021) work was used as fundamental tool to set up the inputs of the simulation and then, compare the experiments results with their previous results. Simulations were labelled as Basis (B1, B2, B3) in order to identify the OZone inputs and their results to compare the equivalent fire duration of each compartment scenario.

Equivalent fire duration results:

B1 - Traditional Concrete compartment = 54 minutes - (Van Herpen, 2021)
B2 - Initial CLT Compartment = 101 minutes - (Van Herpen, 2021)
B3 - Laboratory Experiments CLT Compartment = 100 min

Due to the manual spreadsheet input of the CLT rate of heat release (RHR) based on the experiments' data, the Ozone software interface did not allow the input of an extended fire duration as a combustion model. In practice, that means that the RHR in simulation B3, is segmented in two parts: the compartment and partly in external flames, leading to a significant RHR release in the form of flames coming out of the compartment. This represents a significant setup variation of the simulation, in comparison to B1 and B2 previous simulations where all energy is released inside the own compartment.

In that way, a better performance of the B3 simulation would be acquired if the possibility of an external flaming combustion is set to occur during the fire compartment scenario. With that assumption, the equivalent fire duration of the CLT compartment decreases and ends at 88 minutes. The resulting graphs for B1 and B2 simulations are shown in Figure 79, as the comparison parameters for B3 simulation, based on Van Herpen, R. (2021) outcomes.

The resulting graph of the experiments results simulation (B3), in terms of equivalent fire duration (fire standard curve) and the temperature of the compartment (as the natural fire curve) is shown in Figure 80, displaying 6000 seconds (100 minutes) as the total fire duration of the compartment without the aforementioned external flaming and no fire repressive action.

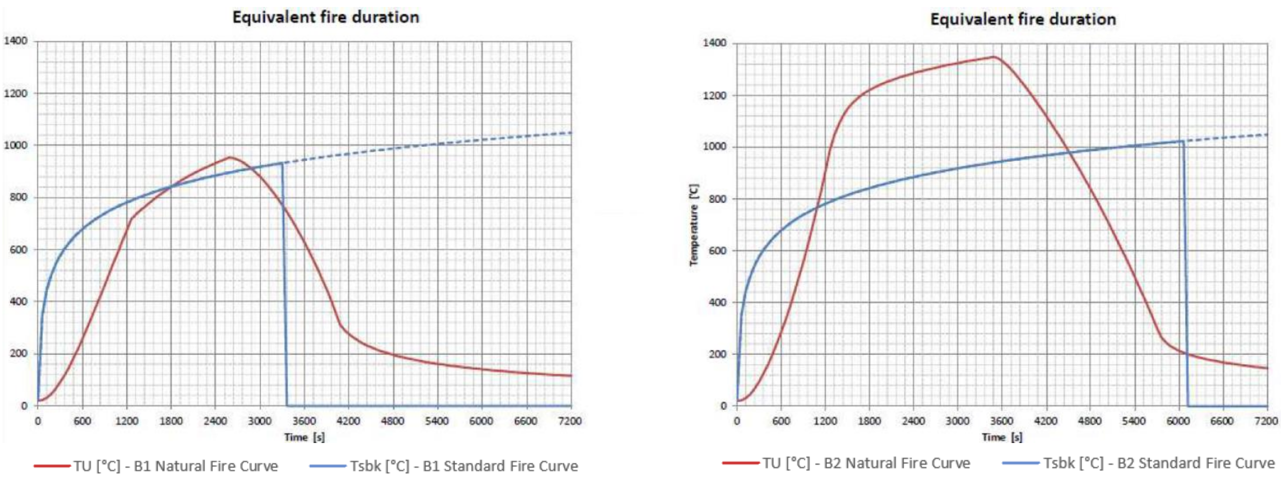


Figure 79. Equivalent fire duration graphs for Basis 1 (left) and Basis 2 (right). (Van Herpen, 2021).

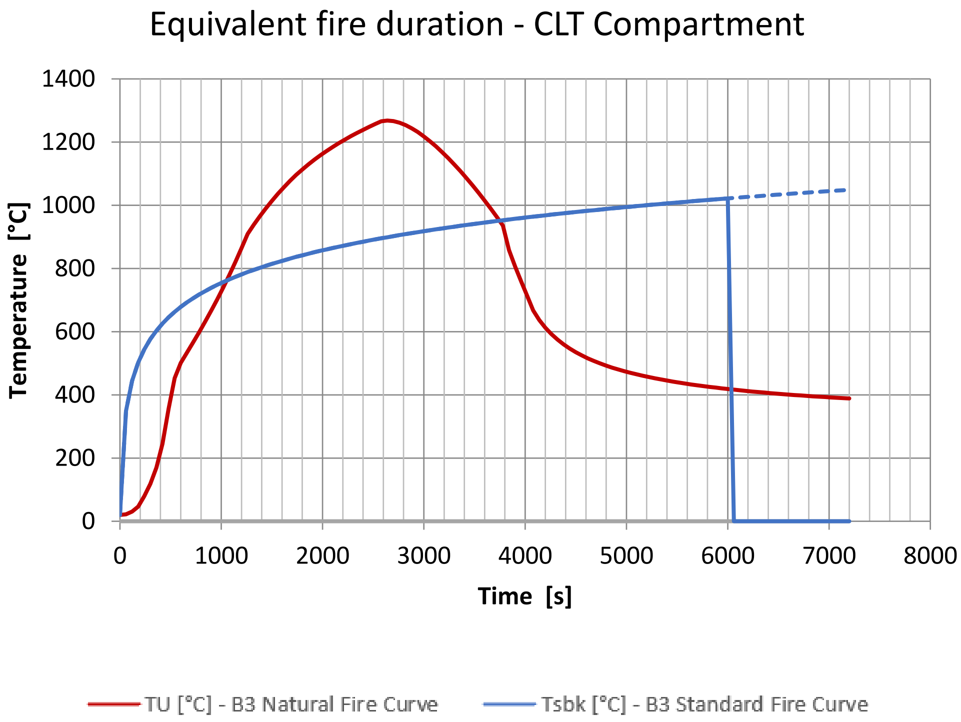


Figure 80. Equivalent fire duration graph for Basis 3 OZone simulation. (Van Herpen, 2022).

2. LOD1 (Local Fire – Material)

Based in the laboratory results and the simulation, further investigation is needed to give an overwhelming answer about the possibility of resilience in CLT constructions. As previously mentioned, self-extinguishment was not actually achieved during the experiments, initial hints of this process were found based on a sustained smouldering combustion and the considerable mass loss rate reduction during the second series of experiments.

The very first response against fire, as Lines of Defence 1 understood as the usage of unprotected cross laminated timber, still demands deeper research. Investigations such as Schmidt, L. (2020), suggested that the use of unidirectional glass fibre mat as coating material for CLT constructions, would lead to a more efficient char fall-off prevention. In that way, the self-extinguishment process could be triggered in time and the architectural value of the wood grain, as a finishing material, would be preserved due to the transparent character of glass fibre.

3. LOD2 Design (Compartment Fire – Detailing)

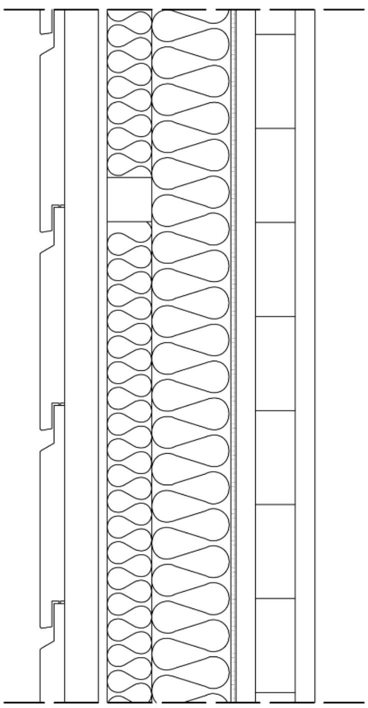
Following the objectives and the scope of the research, from the architectural point of view the proposal of a robust compartment detailing, started to play a fundamental role based on the aforementioned results. As self-extinguishment needs further investigations to understand the right conditions to be triggered, the prevention of fire spread from one compartment (room) to another, becomes a determining tool to allow the usage of unprotected CLT as a construction and finishing material, defending the architectural value of wood.

Lines of Defence 2 then, represent an opportunity for the compartmentation of fire without an automatic response such as sprinklers. The addition of fire insulation to the normative thermal and acoustic insulation, would result in a better fire barrier of the partitions constructions, preventing fire propagation to further spaces of the building. The aforementioned can be understood as the design of robust detailing, talking about fire barriers and the possibility of a resilient building linked to sustainability.

As mentioned at the beginning of the report, the most common way to strengthen, from the fire risk point of view, a cross laminated timber construction would be the one of adding a coating protection e.g., fire-resistant plasterboard. Building with wood, without showing the material itself, from the architectural point of view of this investigation, would lead to a contradiction talking about finishing materials.

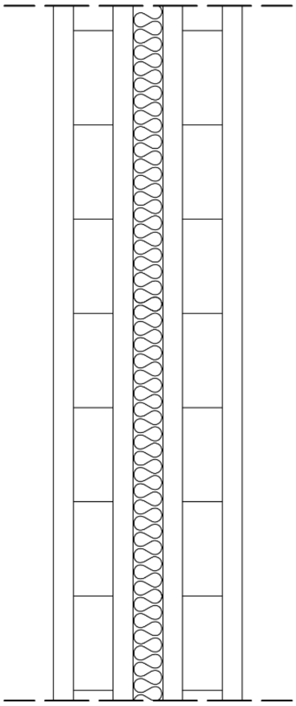
Contemporary architectural design pays special attention to colour, texture and the atmosphere feeling a material would produce in a constructing space. In that way, putting aside the undeniable advantages of a fire-resistant plasters, coating a wood surface would result in a lost opportunity to display a cosy character inside space. Fire resistance can also be achieved in other ways, even with combustibles materials such as timber. Robust detailing, as the use of novel non-flammable insulating materials in strategic locations, could provide a reliable solution.

The strategic detailing corresponding to a better Lines of Defence 2 response, was identified to be located in four different elements of the CLT compartment construction: External walls, partition walls, vertical joint flooring to load-bearing compartment separating walls and external walls to compartment flooring joint. The proposal of the corresponding details for LOD 2 are shown in the following Figures.



Section Key - From outside in (mm):
22 external cladding- 34 battens- Wind protection
55 studs and Rockwool - 100 Rockwool Soffit Slab insulation
Vapour retarder- 80 CLT panel

Figure 81. Detail 1 - CLT external wall, based on (Gustafsson, 2019).



Section Key - From outside in (mm):
80 CLT panel
50 Rockwool Soffit Slab insulation
80 CLT panel

Figure 82. Detail 2 - CLT partition wall, based on (Gustafsson, 2019).

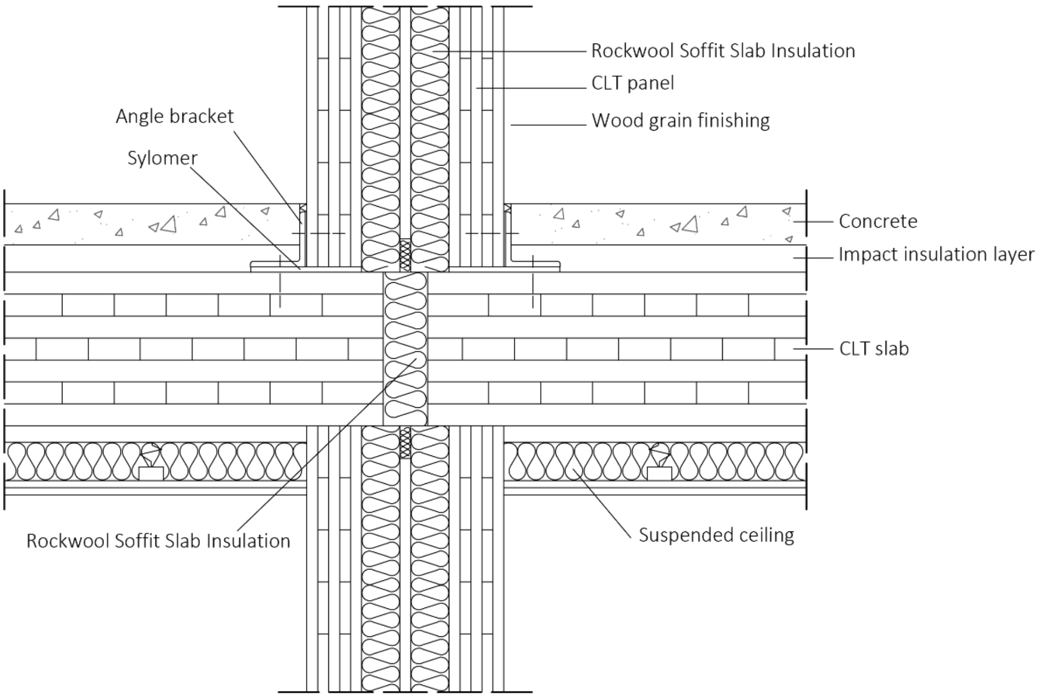


Figure 83. Detail 3 - CLT vertical cross section, based on (Gustafsson, 2019).

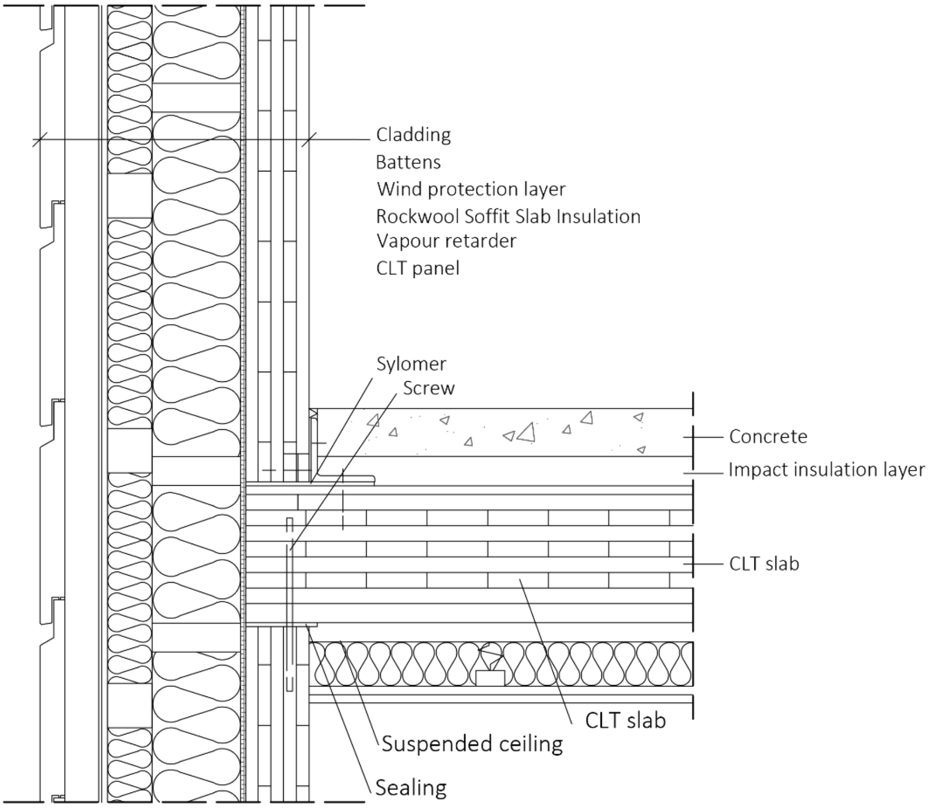


Figure 84. Detail 4 - CLT external wall to compartment flooring joint, based on (Gustafsson, 2019).

Improving the detailing of CLT constructions, through the implementation of non-flammable semi-rigid thermal and acoustic insulation e.g., Rockwool Soffit Slab, could lead to a better fire performance of the compartment. Due to the strength of the details (robustness), the construction would be able to provide a better scenario for self-extinguishment, as the compartment itself would work as a fire container.

By preventing further flame spread and plotting the right circumstances in which all combustible materials, aside the construction elements, are fully consumed inside, the CLT compartment could set the conditions for a very slow smouldering combustion of wood that would trigger self-extinguishment. Moreover, the single improvement of containing fire in a single space, could be understood as a resilient feature. Having a controlled fire inside a combustible structure such as CLT housing, would lead to focalized damage and faster external responses and thus, lower recovery times without compromising the complete structural functionally of the building.

4. Conclusions

Based on the laboratory experiments results, the equivalent fire duration simulation and the cross laminated timber compartment details design, it is possible to conclude:

- Giving the scenario in which there is a variable fire load inside of the compartment, assuming that after 30 minutes all combustible materials are burnt and just the unprotected CLT construction is burning in the form of radiation heat flux coming from other construction smouldering elements, walls, ceiling and from the soot particles in the gas mass inside the compartment, it could be possible to have self-extinguishment.

- Based on the char layer temperatures registered during the tests, that displayed lower values than the expected temperatures of a constant radiation heat flux e.g., 200°C matching 2.5 k/m^2 when the radiant panel was providing 5, 10 and 15 kW/m^2, it is possible to suggest self-extinguishment after the variable fire load is combusted and the fire compartment is well ventilated, as both types (adhesive) of cross laminated timber specimens, in the second series of experiments were passing through a smouldering combustions with considerably lower temperatures.

- Wall, floor and ceiling detailing (LOD2) of unprotected cross laminated timber constructions, becomes a fundamental fire barrier that aims to contain the fire inside the compartment. The aforementioned, added to the assumption that all the combustible materials inside the room are burnt after certain time, could set the right circumstances to trigger a self-extinguishment process. Special attention should be also given to the joint connection between the compartment external wall e.g., façades, and the compartment floor in order to prevent fire spread towards adjoining constructions. An efficient fire compartmentation should prevent internal and external propagation.

- Fire compartmentation, as the improvement of contain fire in a single space, could be understood as a resilience hint. Under the fire resilience definition, the building would be able to maintain the majority of its functionality and would return quickly to its original condition, based on the fire damage limitation (localized fire) and the possibility of a more efficient and fast external response to the specific burning area.

- Fostering unprotected cross laminated timber as a resilient material still requires deeper investigation. Timber connection to sustainably is undeniable, based on the known renewable character and the recycling process. From the fire risk point of view, the material itself could represent a step forward of the conventional sustainability definition. The mitigation of the environmental, social and economic impacts that a CLT building fire can produce, represents the real opportunity to set further sustainable features, based on the material own mechanical properties and thus, setting the path to recover wood's architectural value as a reliable construction and finishing material.

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Figure 47., 48., Berdugo Calderón, A.F. (2022). Own footage.

Figure 49., Berdugo Calderón, A.F. (2021). Own footage.

Figure 50., 51., Berdugo Calderón, A.F. (2022). Own footage.

Figure 52., Berdugo Calderón, A.F. (2021). Own footage.

Figure 53., 54., Berdugo Calderón, A.F. (2022). Own footage.

Figure 55., Berdugo Calderón, A.F. (2021). Own footage.

Figure 56., 57., Berdugo Calderón, A.F. (2022). Own footage.

Figure 58., Berdugo Calderón, A.F. (2021). Own footage.

Figure 59., 60., Berdugo Calderón, A.F. (2022). Own footage.

Figure 61., Berdugo Calderón, A.F. (2021). Own footage.

Figure 62., 63., Berdugo Calderón, A.F. (2022). Own footage.

Figure 64., Berdugo Calderón, A.F. (2021). Own footage.

Figure 65., 66., Berdugo Calderón, A.F. (2022). Own footage.

Figure 67., Berdugo Calderón, A.F. (2021). Own footage.

Figure 68., 69., 70., 71., 72., Berdugo Calderón, A.F. (2022). Own footage.

Figure 73., 74., 75., 76., 77., Berdugo Calderón, A.F. (2022). Own footage.

Figure 78., Van Herpen, Ruud. (2021). Is woningbouw in CLT 'fire resilient'?. BrandVeilig.com Magazine, 02, May. Page 4, Figure 3. Isometry of the fire compartment (apartment).

Figure 79., Van Herpen, Ruud. (2001). Is woningbouw in CLT 'fire resilient'?. BrandVeilig.com Magazine, 02, May. Page 5, 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 80., Van Herpen, Ruud. (2002). OZone Simulation Basis 3 (B3).

Figure 81., 82., 83., 84., Berdugo Calderón, A.F. (2022). Own footage based on Gustafsson, A. (2019). The CLT Handbook CLT structures – facts and planning. Svenskt Trä. ISBN 978-91-983214-4-3. Page 123, Table 6.7 Selection of external wall designs. Page 124, Table 6.8 Selection of partition wall designs. Page 105, Figure 5.14 Vertical section for building with high demands, regarding sound insulation. Joint flooring to load-bearing apartment separating wall. Page 104, Figure 5.11 Vertical section for building without higher requirements. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/clt-handbook2019-eng-m-svensk-standard-2019.pdf.

APPENDIX

Appendix

A Measurement Spreadsheets

Measurement Sheet 1			
Date:	**Sample**	**Test #**	**Experiment #1**
20/12/2021	PU 1	1.1	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
0	4,96	0	White smoke and surface darkening
2	4,90	0,75	**Lighter induced ignition**
4	4,84	1,5	Intense Flames
6	4,84	1,5	Flame Combustion (F.C)
8	4,84	1,5	Horizontal cracks
10	4,84	1,5	Less Flames
12	4,84	1,5	Less Flames
14	4,84	1,5	Less Flames
16	4,82	1,75	Flames located in vertical cracks
18	4,82	1,75	Vertical bottom cracks with flames
20	4,80	2	Vertical bottom cracks with flames
22	4,80	2	Vertical bottom cracks with flames
24	4,80	2	Two vertical cracks with small flames
26	4,80	2	Fading Flames
28	4,80	2	**Smouldering (SM) phase reached**
30	4,80	2	SM phase, constant smoke
32	4,80	2	SM phase, constant smoke
34	4,76	2,5	SM phase, constant smoke
36	4,76	2,5	SM phase, constant smoke
38	4,74	2,75	SM phase, constant smoke
40	4,74	2,75	SM phase, less smoke
42	4,74	2,75	SM phase, less smoke
44	4,72	3	SM phase, less smoke
46	4,72	3	SM phase
48	4,72	3	SM phase
50	4,70	3,25	SM phase
52	4,70	3,25	SM phase
54	4,70	3,25	SM phase
56	4,68	3,5	SM phase
58	4,68	3,5	SM phase
60	4,66	3,75	SM phase
62	4,64	4	SM phase
64	4,62	4,25	SM phase
66	4,60	4,5	SM phase
68	4,58	4,75	SM phase
70	4,58	4,75	SM phase
72	4,56	5	**First lamella complete visual charring**
74	4,54	5,25	Visible delamination craks (right side)
76	4,52	5,5	**Re-ignition (flames), glue layer reached**
78	4,50	5,75	Visible flames coming out from cracks
80	4,40	7	Right side weakening (First lamella 4cm)
82	4,38	7,25	Right side weakening (First lamella 4cm)
84	4,22	9,25	**First lamella fall-off (70% of 4 cm)**
86	4,20	9,5	Lateral burning (left side)
88	4,18	9,75	Visible flames, left side weakening
90	4,06	11,25	**Complete lamella fall-off (100% of 4 cm)**

Measurement Sheet 1			
Date:	**Sample**	**Test #**	**Experiment #1**
20/12/2021	PU 1	1.1	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
92	4,02	11,75	Flame Combustion (F.C)
94	3,98	12,25	Flame Combustion (F.C)
96	3,94	12,75	Flame Combustion (F.C)
98	3,86	13,75	Flame Combustion (F.C)
100	3,80	14,5	Flame Combustion (F.C)
102	3,64	16,5	Flame Combustion (F.C)
104	3,56	17,5	Less visible flames
106	3,48	18,5	Less visible flames
108	3,40	19,5	Less visible flames
110	3,32	20,5	Less visible flames
112	3,24	21,5	Less visible flames
114	3,18	22,25	Less visible flames
116	3,12	23	**Smouldering (SM) phase reached**
118	3,06	23,75	SM phase, constant smoke
120	3,02	24,25	SM - Final weight = 2,60 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

Measurement Sheet 2			
Date:	**Sample**	**Test #**	**Experiment #1**
20/12/2021	ME 1	2.1	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
0	3,20	0	White smoke and surface darkening
2	3,18	0,25	**Lighter induced ignition**
4	3,06	1,75	Intense Flames
6	3,02	2,25	Flame Combustion (F.C)
8	3,00	2,5	Appearance of vertical cracks
10	2,96	3	Very small flames
12	2,94	3,25	Almost Smouldering
14	2,92	3,5	No apparent flames on surface
16	2,90	3,75	No apparent flames on surface
18	2,88	4	Small flames return
20	2,86	4,25	Little flames (vertical cracks)
22	2,86	4,25	Little flames (vertical cracks)
24	2,86	4,25	Little flames (vertical cracks)
26	2,84	4,5	Fading Flames
28	2,82	4,75	Fading Flames
30	2,82	4,75	**Smouldering (SM) phase reached**
32	2,82	4,75	SM phase, constant smoke
34	2,78	5,25	SM phase, constant smoke
36	2,78	5,25	SM phase, constant smoke
38	2,78	5,25	SM phase, constant smoke
40	2,78	5,25	SM phase, constant smoke
42	2,78	5,25	SM phase, constant smoke
44	2,78	5,25	Apparent reignition (visible flames, cracks)
46	2,78	5,25	Small flames return
48	2,78	5,25	Small flames and smoke
50	2,78	5,25	Small flames and smoke
52	2,78	5,25	Small flames and smoke
54	2,78	5,25	Small flames and smoke
56	2,78	5,25	Small flames and smoke
58	2,76	5,5	Visible flames leaking out vertical cracks
60	2,76	5,5	Visible flames leaking out vertical cracks
62	2,76	5,5	Visible flames leaking out vertical cracks
64	2,76	5,5	Visible and constant flame inside cracks
66	2,76	5,5	**Re-ignition (flames), glue layer reached**
68	2,76	5,5	Flame Combustion (F.C)
70	2,76	5,5	Big flames on the right side
72	2,74	5,75	Flame Combustion (F.C)
74	2,74	5,75	Flame Combustion (F.C)
76	2,74	5,75	**First lamella complete visual charring**
78	2,70	6,25	Flame Combustion (F.C)
80	2,70	6,25	Flame Combustion (F.C)
82	2,68	6,5	Flame Combustion (F.C)
84	2,68	6,5	Left side big flame combustion
86	2,66	6,75	Flame Combustion (F.C)
88	2,62	7,25	Left side big flame combustion
90	2,60	7,5	Flame Combustion (F.C)

Measurement Sheet 2			
Date:	**Sample**	**Test #**	**Experiment #1**
20/12/2021	ME 1	2.1	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
92	2,58	7,75	Flame Combustion (F.C)
94	2,54	8,25	Flame Combustion (F.C)
96	2,54	8,25	Flame Combustion (F.C)
98	2,50	8,75	Flame Combustion (F.C)
100	2,50	8,75	Flame Combustion (F.C)
102	2,48	9	Diagonal F.C
104	2,46	9,25	Intense flame combustion
106	2,44	9,5	Intense flame combustion
108	2,42	9,75	Intense flame combustion
110	2,36	10,5	**Complete lamella fall-off (100% of 3 cm)**
112	2,34	10,75	Less visible flames, still F.C
114	2,32	11	Less visible flames, still F.C
116	2,28	11,5	Less visible flames, still F.C
118	2,26	11,75	Less visible flames, still F.C
120	2,22	12,25	F.C - Final weight = 1,30 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

Measurement Sheet 3			
Date:	**Sample**	**Test #**	**Experiment #1**
21/12/2021	PU 2	1.2	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
0	4,94	0	White smoke and surface darkening
2	4,90	0,5	**Lighter induced ignition**
4	4,84	1,25	Intense Flames
6	4,84	1,25	Intense Flames
8	4,82	1,5	Flame Combustion (F.C)
10	4,82	1,5	Less Flames
12	4,82	1,5	Horizontal cracks
14	4,82	1,5	Vertical bottom cracks with flames
16	4,80	1,75	Vertical bottom cracks with flames
18	4,78	2	Vertical bottom cracks with small flames
20	4,78	2	Fading Flames
22	4,72	2,75	**Smouldering (SM) phase reached**
24	4,70	3	SM phase, constant smoke
26	4,68	3,25	SM phase, constant smoke
28	4,66	3,5	SM phase, constant smoke
30	4,60	4,25	SM phase, less smoke
32	4,58	4,5	SM phase
34	4,56	4,75	SM phase
36	4,50	5,5	SM phase
38	4,46	6	SM phase
40	4,46	6	SM phase
42	4,40	6,75	SM phase
44	4,38	7	SM phase
46	4,34	7,5	SM phase
48	4,32	7,75	SM phase
50	4,28	8,25	SM phase
52	4,24	8,75	SM phase
54	4,22	9	SM phase, more smoke
56	4,20	9,25	SM phase, more smoke
58	4,20	9,25	SM phase, more smoke
60	4,16	9,75	SM phase, constant smoke
62	4,14	10	SM phase
64	4,12	10,25	SM phase
66	4,10	10,5	SM phase
68	4,06	11	SM phase
70	4,04	11,25	SM phase
72	4,04	11,25	Visible delamination craks (first lamella)
74	4,02	11,5	Almost complete charring (left side view)
76	4,02	11,5	**First lamella complete visual charring**
78	4,00	11,75	Visible delamination craks (left side)
80	3,98	12	SM phase, big cracks
82	3,98	12	SM phase, big cracks
84	3,98	12	SM, top side weakening, close to fall-off
86	3,98	12	SM, top side weakening, close to fall-off
88	3,96	12,25	**Re-ignition (flames), glue layer reached**
90	3,76	14,75	**Complete lamella fall-off (100% of 4 cm)**

Measurement Sheet 3			
Date:	**Sample**	**Test #**	**Experiment #1**
21/12/2021	PU 2	1.2	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
92	3,76	14,75	Flame Combustion (F.C)
94	3,74	15	Flame Combustion (F.C)
96	3,72	15,25	Flame Combustion (F.C)
98	3,70	15,5	Intense Flame combustion
100	3,68	15,75	Intense Flame combustion
102	3,66	16	Intense Flame combustion
104	3,64	16,25	Intense Flame combustion
106	3,60	16,75	Intense Flame combustion
108	3,56	17,25	One big flame
110	3,52	17,75	Flame Combustion (F.C)
112	3,48	18,25	Flame Combustion (F.C)
114	3,44	18,75	Less Flames
116	3,38	19,5	Two small flames, vertical cracks
118	3,32	20,25	**Smouldering (SM) phase reached**
120	3,26	21	SM - Final weight = 2,36 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

Measurement Sheet 4			
Date:	**Sample**	**Test #**	**Experiment #1**
21/12/2021	ME 2	2.2	120 min. At 25 kW/m^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
0	3,14	0	White smoke and surface darkening
2	3,12	0,25	**Lighter induced ignition**
4	3,10	0,5	Intense Flames
6	3,08	0,75	Flame Combustion (F.C)
8	3,04	1,25	Less Flames, top horizontal crack
10	3,04	1,25	Bottom Flames
12	3,04	1,25	Vertical cracks with flames
14	3,04	1,25	Less flames and constant smoke
16	3,04	1,25	Fading Flames
18	3,04	1,25	**Smouldering (SM) phase reached**
20	3,04	1,25	SM phase, constant smoke
22	3,02	1,5	SM phase, constant smoke
24	3,02	1,5	SM phase, constant smoke
26	3,00	1,75	SM phase, constant smoke
28	3,00	1,75	SM phase, constant smoke
30	2,98	2	SM phase, constant smoke
32	2,96	2,25	SM phase, lateral smoke
34	2,92	2,75	SM phase, lateral smoke
36	2,92	2,75	SM phase
38	2,90	3	SM phase
40	2,90	3	SM phase
42	2,88	3,25	SM phase
44	2,88	3,25	SM phase
46	2,86	3,5	SM phase
48	2,86	3,5	SM phase
50	2,86	3,5	SM phase
52	2,84	3,75	SM phase
54	2,84	3,75	SM phase
56	2,84	3,75	SM phase
58	2,80	4,25	SM phase
60	2,80	4,25	SM phase
62	2,78	4,5	SM phase, cracking noises
64	2,78	4,5	SM phase, cracking noises
66	2,78	4,5	SM phase, cracking noises
68	2,78	4,5	SM phase, cracking noises
70	2,76	4,75	**Re-ignition (flames), glue layer reached**
72	2,70	5,5	**First lamella fall-off (30% of 3 cm)**
74	2,70	5,5	Flame Combustion (F.C)
76	2,70	5,5	Less Flames
78	2,70	5,5	Less Flames, smoke
80	2,70	5,5	Less Flames, smoke
82	2,68	5,75	Small centre bottom flame, smoke
84	2,68	5,75	Small centre bottom flame, smoke
86	2,66	6	Small centre bottom flame, smoke
88	2,66	6	Small centre bottom flame, smoke
90	2,62	6,5	Lateral small flames

Measurement Sheet 4			
Date:	**Sample**	**Test #**	**Experiment #1**
21/12/2021	ME 2	2.2	120 min. At 25 kW/m²
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m²**	**Notes**
92	2,62	6,5	Small bottom flame
94	2,62	6,5	Small bottom flame
96	2,60	6,75	Small bottom flame, smoke
98	2,58	7	Small bottom flame, smoke
100	2,58	7	Visible flames, left side weakening
102	2,58	7	Visible flames, left side weakening
104	2,58	7	**Lamella fall-off (25% of 3 cm)**
106	2,48	8,25	**Backside ignition**
108	2,48	8,25	SM phase for the backside
110	2,40	9,25	**Complete lamella fall-off (100% of 3 cm)**
112	2,38	9,5	**Frontside Re-ignition (flames)**
114	2,36	9,75	Flame Combustion (F.C)
116	2,34	10	Fading Flames
118	2,30	10,5	**Smouldering (SM) phase reached**
120	2,26	11	SM - Final weight = 1,10 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

Measurement Sheet 5			
Date:	**Sample**	**Test #**	**Experiment #2**
22/12/2021	PU 3	3	30' - 25 kW/m² / 60' - 15 kWm²
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m²**	**Notes**
0	4,88	0	White smoke and surface darkening
2	4,86	0,25	**Lighter induced ignition**
4	4,84	0,5	Intense Flames
6	4,84	0,5	Flame Combustion (F.C), horizontal crack
8	4,84	0,5	Less Flames
10	4,80	1	Bottom flames, vertical crack
12	4,80	1	Bottom flames, vertical crack flames
14	4,80	1	Bottom flames, vertical crack flames
16	4,76	1,5	Bottom flames, vertical crack flames
18	4,76	1,5	Bottom flames, vertical crack flames
20	4,74	1,75	Small bottom flames
22	4,74	1,75	Small bottom flames
24	4,72	2	Very small flame in vertical crack
26	4,70	2,25	Fading Flames
28	4,68	2,5	**Smouldering (SM) phase reached**
30	4,66	2,75	**Rfx switch from 25 kW/m² to 15 kW/m²***
32	4,64	3	SM phase, constant smoke
34	4,62	3,25	SM phase, constant smoke
36	4,58	3,75	SM phase, constant smoke
38	4,56	4	SM phase, constant smoke
40	4,54	4,25	SM phase, constant smoke
42	4,52	4,5	SM phase, constant smoke
44	4,48	5	SM phase, constant smoke
46	4,46	5,25	SM phase, constant smoke
48	4,44	5,5	SM phase, constant smoke
50	4,42	5,75	SM phase, constant smoke
52	4,40	6	SM phase, big bottom crack
54	4,36	6,5	SM phase, more smoke
56	4,34	6,75	SM phase, more smoke
58	4,32	7	**SM phase, edges delamination**
60	4,30	7,25	SM phase, constant smoke
62	4,30	7,25	SM phase, constant smoke
64	4,26	7,75	**SM phase, slow charring process**
66	4,26	7,75	SM phase
68	4,24	8	SM phase 80% visible lateral charring
70	4,24	8	SM phase
72	4,24	8	SM phase
74	4,22	8,25	SM phase, slow charring process
76	4,22	8,25	SM phase
78	4,22	8,25	SM phase
80	4,22	8,25	SM phase
82	4,22	8,25	SM phase
84	4,20	8,5	SM phase 98% visible lateral charring
86	4,20	8,5	**First lamella complete visible charring**
88	4,20	8,5	Secons lamella initial charring
90	4,20	8,5	SM - Final weight = 3,72 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

*** Sample displacement from 22 cm to 34 cm** (CLT front to Panel front)

Measurement Sheet 6			
Date:	**Sample**	**Test #**	**Experiment #2**
22/12/2021	PU 4	4	30' - 25 kW/m² / 60' - 10 kWm²
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m²**	**Notes**
0	4,88	0	White smoke and surface darkening
2	4,86	0,25	**Lighter induced ignition**
4	4,84	0,5	Intense Flames
6	4,82	0,75	Flame Combustion (F.C)
8	4,82	0,75	Less Flames
10	4,82	0,75	Less Flames
12	4,82	0,75	Bottom flames, horizontal crack
14	4,82	0,75	Bottom flames, vertical crack
16	4,82	0,75	Bottom flames, vertical crack flames
18	4,82	0,75	Bottom flames, vertical crack flames
20	4,80	1	Three visible small bottom flames
22	4,80	1	Two visible small bottom flames
24	4,80	1	Fading Flames
26	4,78	1,25	**Smouldering (SM) phase reached**
28	4,76	1,5	SM phase, constant smoke
30	4,72	2	**Rfx switch from 25 kW/m² to 10 kW/m²****
32	4,72	2	SM phase, few smoke
34	4,70	2,25	SM phase, few smoke
36	4,68	2,5	SM phase, few smoke
38	4,66	2,75	SM phase, few smoke
40	4,64	3	SM phase, few smoke
42	4,62	3,25	SM phase, few smoke
44	4,60	3,5	SM phase, few smoke
46	4,58	3,75	**SM phase, very slow middle charring**
48	4,52	4,5	SM phase, constant smoke
50	4,52	4,5	SM phase, constant smoke
52	4,50	4,75	SM phase, constant smoke
54	4,50	4,75	SM phase, constant smoke
56	4,50	4,75	**SM phase, bottom edges delamination**
58	4,48	5	SM phase, constant smoke
60	4,48	5	SM phase, constant smoke
62	4,48	5	SM phase, constant smoke
64	4,48	5	SM phase, constant smoke
66	4,48	5	SM phase, constant smoke
68	4,48	5	SM phase, no visible charring at top side
70	4,48	5	SM phase, constant smoke
72	4,48	5	SM phase, constant smoke
74	4,48	5	SM phase, constant smoke
76	4,48	5	SM phase, constant smoke
78	4,48	5	SM phase, constant smoke
80	4,48	5	SM phase, more smoke
82	4,46	5,25	SM phase, more smoke
84	4,44	5,5	SM phase, more smoke
86	4,42	5,75	SM phase, more smoke
88	4,40	6	SM phase, more smoke
90	4,38	6,25	SM - Final weight = 3,84 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

**** Sample displacement from 22 cm to 42 cm** (CLT front to Panel front)

Measurement Sheet 7			
Date:	**Sample**	**Test #**	**Experiment #2**
23/12/2021	PU 5	5	30' - 25 kW/m^2 / 60' - 5 kWm^2
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m^2**	**Notes**
0	4,84	0	White smoke and surface darkening
2	4,82	0,25	**Lighter induced ignition**
4	4,80	0,5	Intense Flames
6	4,80	0,5	Flame Combustion (F.C), vertical cracks
8	4,78	0,75	Flame Combustion (F.C), vertical cracks
10	4,76	1	Less Flames
12	4,76	1	Less Flames
14	4,74	1,25	Three bottom flames
16	4,74	1,25	Pale Flames
18	4,72	1,5	Pale Flames
20	4,72	1,5	Pale Flames
22	4,70	1,75	Pale Flames
24	4,70	1,75	One bottom flame
26	4,68	2	Fading Flames
28	4,68	2	**Smouldering (SM) phase reached**
30	4,68	2	**Rfx switch from 25 kW/m^2 to 5 kW/m^2*****
32	4,66	2,25	SM phase, constant smoke
34	4,64	2,5	SM phase, less smoke
36	4,64	2,5	SM phase, less smoke
38	4,64	2,5	SM phase, less smoke
40	4,64	2,5	SM phase, few smoke
42	4,64	2,5	SM phase, few constant smoke
44	4,64	2,5	SM phase, few constant smoke
46	4,62	2,75	SM phase, few constant smoke
48	4,62	2,75	SM phase, few constant smoke
50	4,62	2,75	SM phase, few constant smoke
52	4,62	2,75	SM phase, few more smoke right side
54	4,62	2,75	SM phase, more smoke right side
56	4,62	2,75	SM phase, more smoke right side
58	4,62	2,75	SM phase, more smoke right side
60	4,60	3	**SM phase, no apparent charring (visible)**
62	4,60	3	**SM phase, bottom edges delamination**
64	4,60	3	SM phase, more smoke right side
66	4,60	3	SM phase, more smoke right side
68	4,58	3,25	SM phase, very small red dots
70	4,58	3,25	SM phase, more smoke right side
72	4,58	3,25	SM phase, more smoke right side
74	4,58	3,25	SM phase, more smoke right side
76	4,58	3,25	**SM phase, no apparent charring (visible)**
78	4,58	3,25	SM phase, constant smoke
80	4,58	3,25	SM phase, very small red dots
82	4,56	3,5	SM phase, constant smoke
84	4,56	3,5	SM phase, constant smoke
86	4,56	3,5	SM phase, more smoke
88	4,56	3,5	SM phase, more smoke
90	4,54	3,75	SM - Final weight = 3,92 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

***** Sample displacement from 22 cm to 64 cm** (CLT front to Panel front)

Measurement Sheet 8			
Date:	**Sample**	**Test #**	**Experiment #2**
23/12/2021	ME 3	6	30' - 25 kW/m² / 60' - 15 kWm²
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m²**	**Notes**
0	3,06	0	White smoke and surface darkening
2	2,98	1	**Lighter induced ignition**
4	2,86	2,5	Intense Flames
6	2,80	3,25	Intense Flames
8	2,76	3,75	Less Flames
10	2,70	4,5	Flames, vertical cracks
12	2,68	4,75	Flames, vertical cracks
14	2,66	5	Small bottom flames
16	2,62	5,5	Small bottom flames
18	2,58	6	Small bottom flames
20	2,56	6,25	Pale Flames
22	2,56	6,25	Pale Flames
24	2,54	6,5	Fading Flames
26	2,50	7	Fading Flames
28	2,50	7	**Smouldering (SM) phase reached**
30	2,48	7,25	**Rfx switch from 25 kW/m² to 15 kW/m²***
32	2,46	7,5	SM phase, less smoke
34	2,46	7,5	SM phase, few smoke
36	2,46	7,5	SM phase, few smoke
38	2,46	7,5	SM phase, few more smoke left side
40	2,46	7,5	SM phase, few more smoke left side
42	2,46	7,5	SM phase, constant smoke
44	2,46	7,5	**SM phase, bottom edges weakening**
46	2,46	7,5	SM phase, constant smoke
48	2,46	7,5	SM phase, constant smoke
50	2,46	7,5	SM phase, constant smoke
52	2,46	7,5	SM phase, constant smoke
54	2,46	7,5	SM phase, constant smoke
56	2,42	8	**SM phase, bottom edges delamination**
58	2,42	8	SM phase, constant smoke
60	2,42	8	SM phase, constant smoke
62	2,42	8	SM phase, constant smoke
64	2,40	8,25	SM phase, constant smoke
66	2,40	8,25	**SM phase, slow charring process**
68	2,38	8,5	**First lamella visual charring (73%)**
70	2,36	8,75	SM phase, constant smoke
72	2,36	8,75	**SM phase, slow charring process**
74	2,36	8,75	SM phase, constant smoke
76	2,36	8,75	SM phase, less smoke
78	2,36	8,75	SM phase, less smoke
80	2,32	9,25	SM phase, less smoke
82	2,32	9,25	**SM phase, slow charring process**
84	2,32	9,25	SM phase, less smoke
86	2,30	9,5	SM phase, few constant smoke
88	2,30	9,5	SM phase, few constant smoke
90	2,28	9,75	SM - Final weight = 1,88 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

*** Sample displacement from 22 cm to 34 cm** (CLT front to Panel front)

Measurement Sheet 9			
Date:	**Sample**	**Test #**	**Experiment #2**
23/12/2021	ME 4	7	30' - 25 kW/m² / 60' - 10 kWm²
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m²**	**Notes**
0	3,26	0	White smoke and surface darkening
2	3,22	0,5	**Lighter induced ignition**
4	3,16	1,25	Intense Flames
6	3,10	2	Less Flames, horizontal cracks
8	3,06	2,5	Less Flames, horizontal cracks
10	3,04	2,75	Flames, vertical cracks
12	3,00	3,25	Flames, vertical cracks
14	2,96	3,75	Flames, vertical cracks
16	2,94	4	Small bottom flames
18	2,94	4	Small bottom flames
20	2,88	4,75	Small bottom flames
22	2,88	4,75	Two small bottom flames
24	2,86	5	Fading Flames
26	2,84	5,25	**Smouldering (SM) phase reached**
28	2,84	5,25	SM phase, few smoke
30	2,82	5,5	**Rfx switch from 25 kW/m² to 10 kW/m²** **
32	2,80	5,75	SM phase, few smoke, bottom crack
34	2,80	5,75	SM phase, few smoke
36	2,80	5,75	SM phase, few smoke
38	2,80	5,75	SM phase, few more smoke
40	2,78	6	SM phase, few more smoke
42	2,76	6,25	**SM phase, top + bottom straight cracks**
44	2,76	6,25	SM phase, constant smoke
46	2,72	6,75	SM phase, constant smoke
48	2,70	7	SM phase, constant smoke
50	2,68	7,25	SM phase, constant smoke
52	2,66	7,5	SM phase, constant smoke
54	2,66	7,5	**SM phase, side darkening (no charring)**
56	2,62	8	SM phase, constant smoke
58	2,62	8	SM phase, constant smoke
60	2,62	8	SM phase, constant smoke
62	2,60	8,25	SM phase, constant smoke
64	2,60	8,25	SM phase, constant smoke
66	2,58	8,5	**SM phase, side darkening (40%)**
68	2,56	8,75	SM phase, few more smoke left side
70	2,56	8,75	SM phase, few more smoke left side
72	2,54	9	SM phase, constant smoke left side
74	2,52	9,25	SM phase, constant smoke left side
76	2,52	9,25	SM phase, constant smoke left side
78	2,50	9,5	SM phase, constant smoke left side
80	2,48	9,75	SM phase, constant smoke left side
82	2,48	9,75	**SM phase, side darkening (100%)**
84	2,46	10	SM phase, constant smoke left side
86	2,44	10,25	SM phase, constant smoke left side
88	2,44	10,25	SM phase, constant smoke left side
90	2,44	10,25	SM - Final weight = 2,12 kg (dismantled^)

^ Unmounted CLT specimen without the char retained by fire insulation

**** Sample displacement from 22 cm to 42 cm** (CLT front to Panel front)

Measurement Sheet 10			
Date:	**Sample**	**Test #**	**Experiment #2**
23/12/2021	ME 5	8	30' - 25 kW/m² / 60' - 5 kWm²
Recorded Data			
Time (Min.)	**Weight (kg)**	**Mass loss kg/m²**	**Notes**
0	3,14	0	White smoke and surface darkening
2	3,10	0,5	**Lighter induced ignition**
4	3,08	0,75	Intense Flames
6	3,04	1,25	Intense Flames
8	3,04	1,25	Less Flames, horizontal bottom crack
10	3,02	1,5	Flames, vertical cracks
12	3,00	1,75	Flames, vertical cracks
14	3,00	1,75	Three vertical cracks flames, one lateral
16	2,98	2	Two vertical cracks flames
18	2,98	2	Small bottom right flames
20	2,96	2,25	Small bottom right flames
22	2,96	2,25	Small bottom right flames
24	2,94	2,5	Small bottom right flames
26	2,94	2,5	Fading Flames
28	2,92	2,75	**Smouldering (SM) phase reached**
30	2,92	2,75	**Rfx switch from 25 kW/m² to 5 kW/m²*** **
32	2,90	3	SM phase, few smoke
34	2,90	3	SM phase, few smoke
36	2,90	3	SM phase, few smoke
38	2,90	3	SM phase, few more smoke right side
40	2,90	3	SM phase, constant smoke right side
42	2,88	3,25	SM phase, constant smoke right side
44	2,88	3,25	SM phase, constant smoke right side
46	2,88	3,25	SM phase, constant smoke right side
48	2,88	3,25	SM phase, constant smoke right side
50	2,88	3,25	SM phase, constant smoke right side
52	2,88	3,25	**SM phase, no apparent charring (visible)**
54	2,88	3,25	SM phase, constant smoke right side
56	2,88	3,25	SM phase, constant smoke right side
58	2,86	3,5	**SM phase, bottom edge delamination**
60	2,84	3,75	SM phase, constant smoke right side
62	2,82	4	SM phase, constant smoke right side
64	2,80	4,25	SM phase, constant smoke right side
66	2,78	4,5	SM phase, constant smoke right side
68	2,76	4,75	SM phase, constant smoke right side
70	2,76	4,75	SM phase, constant smoke right side
72	2,76	4,75	**SM phase, slow side darkening**
74	2,76	4,75	SM phase, constant smoke right side
76	2,74	5	SM phase, constant smoke right side
78	2,72	5,25	SM phase, constant smoke right side
80	2,70	5,5	SM phase, constant smoke right side
82	2,66	6	SM phase, constant smoke right side
84	2,64	6,25	SM phase, constant smoke right side
86	2,62	6,5	SM phase, constant smoke right side
88	2,60	6,75	SM phase, constant smoke right side
90	2,58	7	SM - Final weight = 2,26 kg (dismantled**^**)

^ Unmounted CLT specimen without the char retained by fire insulation

***** Sample displacement from 22 cm to 64 cm** (CLT front to Panel front)

Fire Resilience of Cross Laminated Timber in Residential Buildings

Exploring a Sustainable Feature