forests

MDPI

Article

Numerical Analysis of Fire Resistance in Cross-Laminated Timber (CLT) Constructions Using CFD: Implications for Structural Integrity and Fire Protection

Nikola Perković *, Davor Skejić and Vlatka Rajčić

Structural Department, Faculty of Civil Engineering, University of Zagreb, 10000 Zagreb, Croatia; davor.skejic@grad.unizg.hr (D.S.); vlatka.rajcic@grad.unizg.hr (V.R.)
* Correspondence: nikola.perkovic@grad.unizg.hr

Abstract: Fire represents a serious challenge to the safety and integrity of buildings, especially timber structures exposed to high temperatures and intense heat radiation. The combustibility of timber is one of the main reasons why regulations strictly limit timber as a building material, especially in multi-storey structures. This investigation seeks to assess the fire behaviour of cross-laminated timber (CLT) edifices and examine the ramifications for structural integrity and fire protection. Utilising computational fluid dynamics (CFD) simulations, critical variables including charring rate, heat emission, and smoke generation were analysed across two scenarios: one featuring exposed CLT and another incorporating protected CLT. The outcomes indicated that protective layers markedly diminish charring rates and heat emission, thereby augmenting fire resistance and constraining smoke dissemination. These revelations imply that CFD-based methodologies can proficiently inform fire protection design paradigms for CLT structures, presenting potential cost efficiencies by optimising material utilisation and minimising structural impairment.

Keywords: fire; timber; HRR; FEM; Eurocode 5; visibility

Citation: Perković, N.; Skejić, D.; Rajčić, V. Numerical Analysis of Fire Resistance in Cross-Laminated Timber (CLT) Constructions Using CFD: Implications for Structural Integrity and Fire Protection. *Forests* **2024**, *15*, 2046. https://doi.org/10.3390/f15112046

Academic Editors: Rafael Rodolfo De Melo, Adriano Reis Prazeres Mascarenhas and Zhichao Lou

Received: 18 October 2024
Revised: 15 November 2024
Accepted: 17 November 2024
Published: 20 November 2024

1. Introduction

Cross-laminated timber (CLT) has experienced considerable acceptance within the construction sector, because it is sustainable and has good structural capacity, but its high natural combustibility creates critical challenges for fire safety. As a product of engineered wood, CLT is composed of multiple layers of timber boards that are adhesively bonded at perpendicular orientations, resulting in a robust, dimensionally stable panel that boasts an enhanced capacity for load bearing [1]. This distinctive arrangement confers numerous benefits over conventional wood products, including augmented stiffness and strength in both axial orientations, thereby rendering it appropriate for use in walls, floors, and roofs across residential, commercial, and even high-rise edifices [2]. Although CLT contributes to reducing the carbon footprint of buildings, its adoption in large-scale construction is hindered by stringent fire safety requirements that present significant challenges to its broader implementation.

Although wood is recognised as a renewable and sustainable resource, it possesses intrinsic flammability. Nevertheless, the fire safety characteristics of CLT constructions present considerable obstacles due to the material's inherent flammability. In contrast to steel or concrete, which exhibit relatively consistent behaviour in response to fire exposure, CLT is capable of sustaining combustion, thereby engendering risks related to fire propagation, structural integrity failure, and the potential for reignition following extinguishment [3]. The fire resistance of CLT is frequently addressed through the formation of char layers on the surface during high-temperature exposure; although this mechanism can decelerate the combustion process, it does not entirely negate the risk of structural failure, particularly under conditions of extended heat exposure [4,5]. To attain the requisite fire resistance, designers may augment the thickness of CLT panels, incorporate protective layers (such as gypsum board), or apply fire-retardant treatments [6,7]. Research indicates that the fire performance of CLT panels may vary inconsistently based on their thickness and layer arrangement, necessitating the implementation of enhanced design and protective measures, such as encapsulation with non-combustible materials [8]. Furthermore, once subjected to charring, CLT may undergo delamination, a phenomenon where heated layers detach, subsequently exposing uncharred wood to flames and further undermining the structural integrity [9]. These issues accentuate the imperative for fire safety design methodologies that are specifically tailored to CLT frameworks, ensuring adherence to building regulations while prioritising occupant safety in mid- and high-rise constructions.

In the context of fire design for CLT, two predominant methodologies are generally employed: prescriptive and performance-based design. The prescriptive approach relies on predefined standards and codes to ensure a certain level of safety, often outlining specific material requirements, dimensions, and construction methods. This approach provides straightforward guidelines but may lack flexibility to adapt to unique design challenges. On the other hand, the performance-based approach focuses on achieving safety goals by analysing the specific fire behaviour of the structure under various scenarios. This approach allows for greater design innovation and can be tailored to the unique properties of CLT, but it requires comprehensive risk assessments and often involves complex simulations to ensure fire resistance. Each methodology presents different advantages and limitations that influence its suitability for CLT applications in fire safety design. Prescriptive design is predicated on predetermined solutions delineated in building codes, which stipulate minimum material thicknesses, protective layers, and various other prerequisites to ensure fire safety. While this methodology offers simplicity and transparency, it may occasionally be excessively conservative and may not fully exploit the intrinsic fire resistance characteristics of CLT [1]. Conversely, performance-based design provides enhanced flexibility by enabling engineers to customise fire safety measures in accordance with the specific attributes of the building, materials, and fire scenario. This approach necessitates the utilisation of advanced analytical tools, such as experimental testing and numerical simulations, to evaluate the actual behaviour of CLT under fire conditions.

In contemporary scholarly discourse, computational fluid dynamics (CFD) has indeed become an essential tool for evaluating the fire behaviour of cross-laminated timber (CLT) materials, particularly due to its ability to provide insights into complex thermodynamic interactions that are otherwise challenging to study through traditional experimental means. Specifically, in this study, CFD enables the detailed analysis of heat propagation and smoke formation within CLT when exposed to fire. By simulating these behaviours, CFD allows for a comprehensive assessment of thermal degradation patterns, charring rates, and the diffusion of combustion gases. This, in turn, facilitates a more accurate understanding of the fire performance of CLT structures, which is crucial for predicting their resilience, enhancing safety standards, and informing design guidelines.

In summary, the use of CFD in this context is indispensable, because it provides a robust framework for predicting critical aspects of CLT behaviour under fire conditions that are essential for structural safety and fire prevention strategies. This depth of analysis is paramount for performance-based fire design, wherein an intricate understanding of fire behaviour is crucial for enhancing the safety and resilience of edifices [6].

The analysis undertaken through CFD entails the modelling of the interactions among fire, thermal energy, and various materials, thereby enabling engineers to forecast the progression of a fire within a CLT framework. This process comprises the simulation of the charring rate of CLT, the thermal distribution across the panel, and the influence of protective coatings or fire-retardant applications. A significant merit of CFD lies in its capacity to encapsulate complex phenomena, such as localised fire spread, the effects of ventilation, and the interactivity between diverse building materials. In the case of CLT structures, CFD simulations serve to enhance fire design by predicting the duration of structural stability under fire conditions, identifying potential vulnerabilities, and assessing diverse fire protection methodologies [10].

Furthermore, CFD simulations are instrumental in examining the efficacy of compartmentalisation and fire barriers within multi-storey timber constructions. Compartmentalisation constitutes a vital component of fire safety protocols in buildings, wherein each segment of the edifice is engineered to restrict the transmission of fire to contiguous zones. In CLT edifices, where the material itself possesses combustibility, the effectiveness of compartmentalisation is critical for confining a fire to a specific area. Through the application of CFD analysis, engineers can simulate a variety of fire scenarios and scrutinise how the architecture of fire barriers, walls, and floors influences the propagation of fire and smoke [6].

While CFD offers substantial insights, it is imperative to acknowledge that the precision of these simulations is contingent upon the reliability of input data, which includes material characteristics, heat release rates, and boundary conditions [11]. Accordingly, empirical testing remains a fundamental element of fire design for CLT. Fire testing furnishes empirical data regarding the charring behaviour, thermal distribution, and structural integrity of CLT under regulated conditions, which can subsequently be utilised to validate and enhance CFD models. By integrating experimental findings with numerical simulations, engineers can formulate more dependable and effective fire design strategies for timber constructions [12]. Subsequent advancements in computational fluid dynamics (CFD) technology, particularly the incorporation of fluid–structure interaction (FSI) models, are likely to provide deeper comprehension of the behaviour of timber structures when subjected to fire conditions, thereby facilitating the development of more sophisticated fire design methodologies [13]. In addition, as innovative fire-retardant treatments and protective coatings for cross-laminated timber (CLT) are formulated, it will be imperative to assess their efficacy and integrate these findings into CFD models to enhance the fire resistance of CLT edifices. Notwithstanding the progress achieved in fire design methodologies and computational fluid dynamics (CFD) analysis, numerous obstacles persist in guaranteeing the fire safety of cross-laminated timber (CLT) structures. A significant obstacle is the deficiency of extensive data concerning the long-term behaviour of CLT under fire conditions, especially in the context of large, multi-storey edifices. Most of the fire testing is performed on smaller-scale specimens, which may not adequately reflect the performance of CLT under realistic environmental conditions. Furthermore, the variability inherent in CLT manufacturing processes, encompassing discrepancies in adhesive formulations, layer thicknesses, and wood species, can influence the fire performance and complicate the standardisation process [14].

Some of the most common CFD models used in fire protection engineering have the following commercial names: FLUENT, PHOENICS, SMARTFIRE, SOFIE, FDS, etc. Some of the above computer tools are particularly suitable for analysing fire engineering problems, such as FDS, SMARTFIRE, and SOFIE, while others are suitable for general use in fluid mechanics analysis with successful application in fire engineering, such as FLUENT. It is always advisable to use commercially proven CFD models that have been validated in many practical applications. Computational fluid dynamics models have found their application in numerous studies dealing with the evolution of fire and smoke and their effects on various aspects of fire occurrence in buildings. Some of the aspects mentioned are the evolution of smoke gases in confined spaces, the effectiveness of natural or mechanical smoke extraction, the resistance of the supporting structure to the fire load, and the time of evacuation of people from the building. PyroSim [15], a graphical interface for FDS [16], is used in this work.

As already mentioned in the introductory section, standardised temperature–time curves have been used for many years to describe a real fire. The result is an oversizing of structural components and very often unnecessary or insufficiently justified fire protection measures for load-bearing timber structures, which requires high financial investment and maintenance. There are many reasons why CFD simulations are not considered in the design of building components:

- high initial investment in computer software
- lack of knowledge in working with computer software
- lack of investor interest in new budgeting methods
- lack of regulations for dimensioning with these calculation methods

Based on the above, the specific objectives of the research are defined to:

- define the characteristic fire scenarios relevant to the assessment of the load-bearing capacity of the timber structure (CLT).
- create a CFD simulation of typical fire scenarios.
- detect the HRR (heat release rate), gas temperatures, and visibility (smoke).
- detect the maximum temperatures on the timber elements.
- evaluate the accuracy of the simulations and the appropriateness in practical applications.
- analyse the influence of temperature on the stability of the timber structure.
- evaluate the load-bearing capacity and resistance of timber structures for different cases—Eurocode 5 (EC5).
- comment on and analyse the currently valid regulations.

This investigation significantly advances the essential domain of fire protection in timber edifices by delivering crucial insights and fundamental data that may facilitate the formulation of efficacious fire safety interventions for structures and various wooden applications. Through the advanced simulation of the response of cross laminated timber under fire conditions, our research addresses a notable deficiency in the existing research of fire safety engineering and bolsters progress in both construction safety regulations and fire protection measures. The outcomes are designed to function as a vital resource for engineers, architects, and policymakers, providing pragmatic direction on augmenting the fire resistance of wood-based infrastructures and contributing to the promotion of safer construction methodologies. Ultimately, this study aspires to enhance the corpus of knowledge in fire protection science, establishing a solid foundation for forthcoming advancements in safety protocols, material treatment methodologies, and building codes specifically tailored for timber construction.

2. Fire Design of Timber Structures

2.1. General

The key parameter influencing the design and construction of residential buildings with load-bearing and fire-resistant timber structures is their combustibility. While the European Union has introduced standardised fire testing methods for the categorisation of different building materials, the responsibility for establishing building regulations that cover the entire structure, including fire safety provisions, lies with the individual member states. Each nation sets its own requirements for fire safety and the applicability of building materials, which vary according to the combustibility characteristics of the structure, the intended function of the building, and the potential level of fire incidents. The current context within the European Union advocates the harmonisation of the assessment standards in all member states and attempts to formulate a uniform framework for the assessment of fire characteristics [17]. In Croatia, the classification with the strictest standards for the fire safety of buildings applies to structures with combustible components, i.e., wooden structures, and other buildings characterised by a high density of people, high fire loads, and high fire heights. The fire safety criteria applicable to wooden residential buildings are inextricably linked to the number of their storeys and the combustibility of their structural components. The characterisation of the structural elements of the building depends on the combustibility of the load-bearing components and the combustibility and installation methods of the insulation and cladding materials applied to these load-bearing structures. According to fire safety standards, buildings are divided into subgroups based on the height of the top floor. As a result, the essential minimum fire resistance of load-bearing and fireresilient elements is established based on these two vital parameters. The modelling and dynamic simulation of fire incidents represent significant methodologies in the planning and assessment of fire safety within structures. Computational models predominantly serve in the evaluation of fire hazards. They forecast the intensity of heat radiation over time, contingent upon the dimensions and arrangement of the fire load, the duration of the fire event, the development of smoke, and the combustion velocity of the fuel. The information generated from such simulations is employed for thorough analyses regarding the design of both passive and active fire protection systems in buildings, the safeguarding of occupants during evacuation procedures, and the enhancement of firefighting efforts. Three principal numerical approaches are utilised to model fires within buildings [14]. The most fundamental methodology entails the development of analytical models for fire progression that rely exclusively on basic principles elucidating the physicochemical reactions and phenomena occurring during combustion. Analytical fire models are distinguished by their rapidity and simplicity of implementation. Nevertheless, their accuracy is constrained by the degree to which they characterise the fire environment. Generally, they provide a foundational framework for more sophisticated computational models in both zonal and dynamic simulations. In contrast, zone models present a more intricate approach to fire simulations [18]. Their methodologies are predicated on the assertion that the fire environment is comprised of two interacting gas layers, which are governed by mathematical equations.

The primary advantage of these models lies in their computational efficiency, facilitating extensive parametric analyses of larger structural entities. Given that these simulations encompass a variety of physical phenomena occurring during a fire event, they possess a heightened capacity to yield more accurate outcomes compared to analytical frameworks [19]. However, the outcomes derived from zonal model simulations frequently encounter significant uncertainties. The most thorough methodology is represented by dynamic simulations [20], which numerically resolve the three-dimensional governing equations for fire-induced fluid dynamics in their differential forms, accommodating various levels of complexity. Software applications such as JASMINE [21], SOFIE [22], and FDS [16] are predominantly employed for their execution. Dynamic simulations necessitate a greater investment of resources to establish model boundary conditions and typically require extended computational durations. These dynamic fire simulations closely approximate actual fire behaviour when the parameters related to the fire load environment, including ignition sources, are optimally configured [23,24]. In the Republic of Croatia, the European regulation is accepted with national additions. The design of timber structures for fire loads is dealt with in the HRN EN 1995-1-2 standard [25]. In the last ten years, we have seen significant research in the field of "fire engineering" globally, which has led to new findings in this field [26]. The main statements of these findings, which are also the recommendations of EUROCODE, are presented below:

- The actual fire load in large, enclosed spaces can not only be defined by the standard fire curve according to ISO834 [27] but the actual strength of a real fire in a room must be checked (calculated) using temperature–time parameter curves.
- When analysing the safety of structures, the influence of a real fire exposure—high temperatures—should be considered as one of the possible effects on the structures, and the sufficient load-bearing capacity of the structure should be demonstrated in a certain required time (R30, R60, R90, . . .).

Based on these considerations and the adopted European standards, this technical paper was written with the aim of investigating the rate of heat release (fire power), the development of the gas temperature, and the fire on a model of a wooden building made of fire-resistant CLT panels. In addition, the aim of this thesis is to perform an advanced numerical analysis of the effects of fire in order to better understand and predict the effects of fire on the wooden elements and the wooden structure as a whole and to evaluate the influence of the geometric and material properties and the methods used to protect the wooden elements from fire on the behaviour of cross-laminated timber (CLT) elements in case of fire.

It is important to note that the results of this work do not imply or critically examine technical solutions for fire protection in the building mentioned.

2.2. Technical Regulations—Croatian Regulations Regulating Fire Protection for Buildings

Fire safety in buildings is governed by various regulations and standards to ensure the safety of people, property, and the environment. These regulations vary from country to country, but there are general principles that apply worldwide.

Planning for the construction and reconstruction of buildings in the field of fire safety in Croatia is regulated by the Building Act [28] (Official Gazette 153/13, 20/17, 39/19, 125/19), the Fire Safety Act [29] (Official Gazette 92/10, 114/22), the Regulation on Fire Resistance and Other Requirements that Buildings Must Meet in Case of Fire (Official Gazette 29/13, 87/15) [30], and various subsidiary acts, recognised codes of practice, and standards.

The regulations in the Republic of Croatia relating to fire safety are divided into three levels. The Fire Safety Act [29] establishes a general system of fire protection that includes the regulation, planning, organisation of cases, implementation of fire protection measures, training, and authorisation to carry out fire protection tasks with the aim of protecting the life, health, and safety of people and animals, as well as protecting material goods, property, nature, and the environment from fire. The Fire Protection Act, like any other law, does not lay down details related to fire protection but rather general principles that are later elaborated through secondary legislation.

The level below the Act is represented in Croatian legislation by ordinances, i.e., secondary Acts that elaborate the provisions of the Acts themselves in detail.

The basic regulation for fire safety is the Regulation on fire resistance and other requirements that buildings must meet in case of fire [30] (Official Gazette 29/13, 87/15), which contains detailed guidelines and requirements regarding various aspects of fire safety in buildings.

The third level consists of European standards that have been adopted and recognised as Croatian, and depending on the topic, they may also contain a national addition, as is the case with most EUROCODEs. The standards only must be applied if they are prescribed by a specific regulation; otherwise, they are applied voluntarily. In the Republic of Croatia, some segments of fire safety, such as the requirements for the design of facilities such as hospitals, retirement and nursing homes, schools, kindergartens, faculties, etc., are not yet covered by Croatian fire safety regulations, so the regulation on fire resistance and other requirements that buildings must meet in the event of fire must be supplemented with modules for buildings of the aforementioned purposes. Until the adoption of Croatian regulations for the fire protection of buildings of the above-mentioned purpose, recognised rules of technology such as the Austrian OIB Directive (Austrian Institute for Building Technology) [31] or NFPA 101 Life Safety Code (National Fire Protection Association) [32] will be applied. Foreign regulations are applied only in those parts of fire protection measures that are not regulated by our regulations, while Croatian regulations must be applied in those parts of fire protection measures that are regulated by Croatian regulations [33].

3. Case Study

The building [25] is a three-storey building, located in the village of Gora, in the town of Petrinja, and it serves as an elementary school (Ivan Goran Kovačić Elementary School). The total width of the building is 27.95 m (with eaves 28.75 m), and the total length is 35.14 m (with eaves 35.60 m). The roof on the first floor of the building (terrace roof) is defined as a single roof with a pitch of 20°. The roof on the top floor of the building is defined as a roof (with bays and ridges at the intersections) with a pitch of 20° and an absolute height of 7.88 m (eaves) and 11.09 m (ridge). The structure of the building is defined by a relatively simple static system, i.e., as a spatial reinforced concrete/timber structure with a timber roof structure on shallow reinforced concrete foundations. The vertical load-bearing elements consist of reinforced concrete walls, steel, and timber columns and timber walls (CLT), while the horizontal load-bearing elements consist of AB slabs; timber beams (KVH, GL, and CLT); and timber slabs connected to the ceiling (CLT), i.e., coupled concrete–timber slabs (CLT-AB) supporting in one direction and connected pitched roof timber slabs (CLT) supporting in one direction.

The building is planned so that it has three above-ground floors, and the height of the floor of the highest floor for people's residence is less than 11 m measured from the height of the outdoor terrain from which the intervention of firefighters, or the evacuation of vulnerable persons, is possible. According to [16,30] (Official Gazette 29/13, 87/15), the building belongs subgroup 4 (ZPS 4). The fire load in certain parts of the building is shown in Table 1. The Austrian guideline TRVB A 126 was used to determine the size of the mobile fire load. The guideline TRVB 100, was used for the size of the immobile fire load. Considering that the load-bearing structure of the school building is made of cross-laminated timber, a value of 1100 MJ/m^2 was taken for the size of the immobile fire load.

Table 1. Fire load.

Area	Mobile Fire Load (MJ/m^2)	Immobile Fire Load (MJ/m^2)	Total (MJ/m^2)
Classroom	300	1100	1400
Office	700	1100	1800
Library	727	1100	1727
Boiler room	400	0	400
Kitchen	500	1100	1600

3.1. CFD Analysis

Fire Dynamics Simulator (FDS) software [16] operates utilising a computational fluid dynamics model. In the context of the FDS simulation, the three-dimensional environment is partitioned into diminutive rectangular volumes. Within these volumes, the gaseous variables are regarded as homogeneous yet exhibit temporal variability. To derive the dynamics, FDS employs the resolution of the Navier–Stokes equations through the implementation of Large Eddy Simulation (LES), which facilitates the simulation of turbulent flows. A hybrid flow model is employed to account for combustion reactions [15]. Heat transfer occurs to solid surfaces alongside fluid movement. The primary benefit of this methodology is its capacity to accommodate variations in fire parameters while yielding insights regarding heat loading. Computational fluid dynamics (CFD) models are capable of simulating fire incidents and their repercussions and the interaction of fire with various safety systems (including fire ventilation, electrical signalling, and fire suppression systems), as well as the impact of fire effects on human movement within the structure. The mathematical foundation of the FDS model comprises four equations, three of which are classified as partial differential equations:

Conservation of mass:

$$\frac{\partial_\rho}{\partial_t} + \nabla \cdot \rho_u = \dot{m}_b^m \tag{1}$$

Conservation of angular momentum:

$$\frac{\partial}{\partial_t} \cdot (\rho_u) + \nabla \cdot \rho_{uu} + \nabla_p = p_g + f_b + \nabla \cdot \pi_{ij} \tag{2}$$

Conservation of energy:

$$\frac{\partial}{\partial_t} \cdot (\rho_{hs}) + \nabla \cdot \rho_{hs} \cdot u = \frac{D_p}{D_t} + \dot{q}^m - \dot{q}_b^m - \nabla \cdot \dot{q}^n + \varepsilon \tag{3}$$

Equation of state:

$$p = \frac{pRT}{\overline{W}} \tag{4}$$

where ρ—density [kg·m^{-3}], u—(u, v, w) space vector, p—pressure [N·m^{-2}], f_b—external force vector, τij—electromagnetic tensor, h_s—enthalpy density, q_b—heat transfer processes inside the droplet, q'''—rate of heat release per unit volume, q''—conduction heat flow, R—universal gas constant, T—temperature, W—molecular weight, t—time, g—gravitational acceleration, and ε—speed of kinetic energy during transformation into thermal energy.

The spatial model was developed utilising the PyroSim 2023 software platform [15], which functions as the graphical interface for Fire Dynamics Simulator (FDS) software [16] and facilitates the modification and management of the input parameters.

In this study, a predefined pyrolysis model is employed. Predefined pyrolysis is conventionally utilised to forecast temperature variations and the dynamics of smoke movement within a specified fire-related environment. To execute these simulations, it is feasible to delineate a time-dependent heat release rate (HRR) and designate the spatial domain where this HRR will manifest. The FDS algorithm employs this information to ascertain the volume of combustible gases that will infiltrate the designated area and subsequently ignite. Alternatively, one may specify the time-dependent influx of combustible gases entering the simulated region. This predefined pyrolysis model can be instantiated alongside a SURF "burner" applied to a VENT or surface. Upon attaining a specific ignition temperature, the surface is transformed into a source for the emission of gaseous fuel. The heat emission profile may also be configured to cease after a predetermined mass of the combusting surface has been fully consumed. This pyrolysis model necessitates an assumption regarding the heat release rate of the burning material, which can be derived from the literature [34,35] and various fire testing protocols [36]. In the present investigation, both the existing literature and cutting-edge methodologies were consulted.

3.2. Three-Dimensional Model

Based on the architectural and structural drawings and a detailed 3D model (Figure 1), a simplified spatial (3D) model of the object was created. In the pursuit of establishing a computationally efficient and structurally representative three-dimensional model, numerous simplifications were implemented on the intricate geometry of the original object. To commence, negligible surface attributes, including minor indentations and textural elements, were excluded, as they did not exert a substantial influence on the model's functional or structural integrity, yet would have contributed to an increase in computational demands. Furthermore, non-essential internal elements, particularly those extraneous to the primary structural or functional considerations, were deliberately omitted. Moreover, certain curved and complex configurations were approximated through the utilisation of more straightforward geometric shapes to mitigate the intricacy of the mesh. This methodology facilitated the preservation of critical structural characteristics and the overall silhouette while permitting smoother simulations and diminishing the processing demands. Notwithstanding these simplifications, the model maintains a commendable degree of precision for the primary analyses designated for this investigation. These alterations were meticulously deliberated to ascertain that the model would still faithfully encapsulate the fundamental attributes of the object, thereby enabling efficient and trustworthy analyses while sustaining the pivotal components of the actual design.

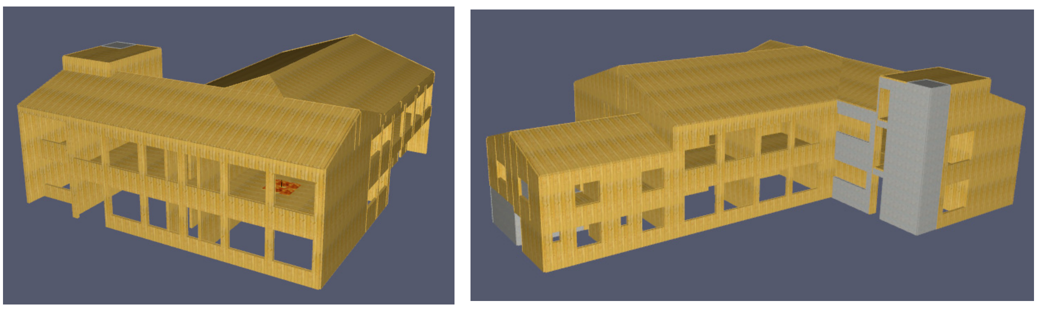


Figure 1. Three-dimensional model—PyroSim.

The resulting 3D model was adapted to the needs and format acceptable for the PyroSim [15] program package, in which the simulation of the development of fire and smoke is carried out and the temperatures on the surfaces are determined.

In a combustion scenario, surfaces are subjected to both radiant and convective heat. A portion of this thermal energy is conveyed to the solid material as a heat flux. These surfaces may comprise multiple layers of various materials, which can experience thermal decomposition reactions during the process of heat conduction, consequently altering their chemical makeup. The Fire Dynamics Simulator (FDS) posits that conductive heat travels perpendicularly to the solid surface and can be modelled using a one-dimensional heat conduction equation. However, this one-dimensional assumption has inherent limitations, as it neglects the radial spread of heat and the heating effects on multiple facets of a specific surface or element. FDS incorporates "obstacles", defined as three-dimensional solid entities that "impede" the flow of energy. This definition encompasses walls, floors, ceilings, and any other component of the structural assembly.

3.3. Mesh

Numerical mesh generation was also performed in PyroSim [15]. Below are the rules that guided this work (Figure 2).

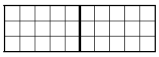
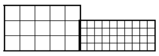
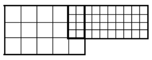
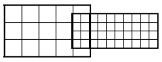
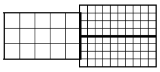
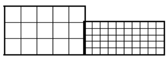
	This is the ideal type of mesh alignment
	This is allowed, as long as there is a whole number of fine cells opposite each rough cell and every rough cell only "sees" fine cells from one mesh.
	This is allowed but questionable.
	This is not allowed, because each large the cell must be completely covered with small cells.
	It is not allowed, because it exists as a coarse cell that "sees" fine cells of two different meshes.
	This is not allowed, because there is an incomplete number of fine cells opposite each coarse cell.

Figure 2. Mesh alignments [16].

The numerical meshes for both fire scenarios have a higher resolution in the areas of interest for the analysis (fire source, wood panel and wall construction, fresh air supply, etc.), which is a characteristic of the so-called "unstructured" numerical meshes.

Specifically, the numerical mesh (Figure 3) is compressed into control volumes of dimensions 0.1 m × 0.1 m × 0.1 m in the area of interest, while the rest of the object is defined in control volumes of dimensions from 0.2 m × 0.2 m × 0.2 m to 0.4 m × 0.4 m × 0.4 m.

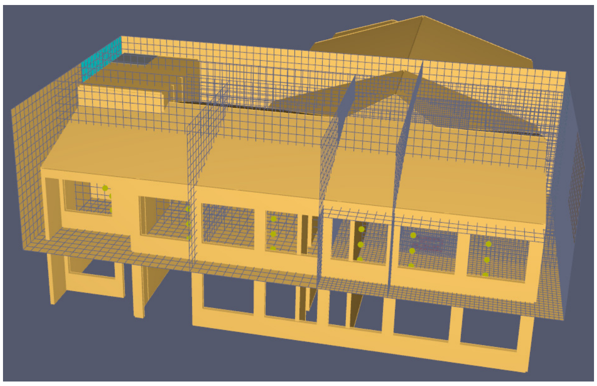


Figure 3. Meshes.

3.4. Input Data and Simulation

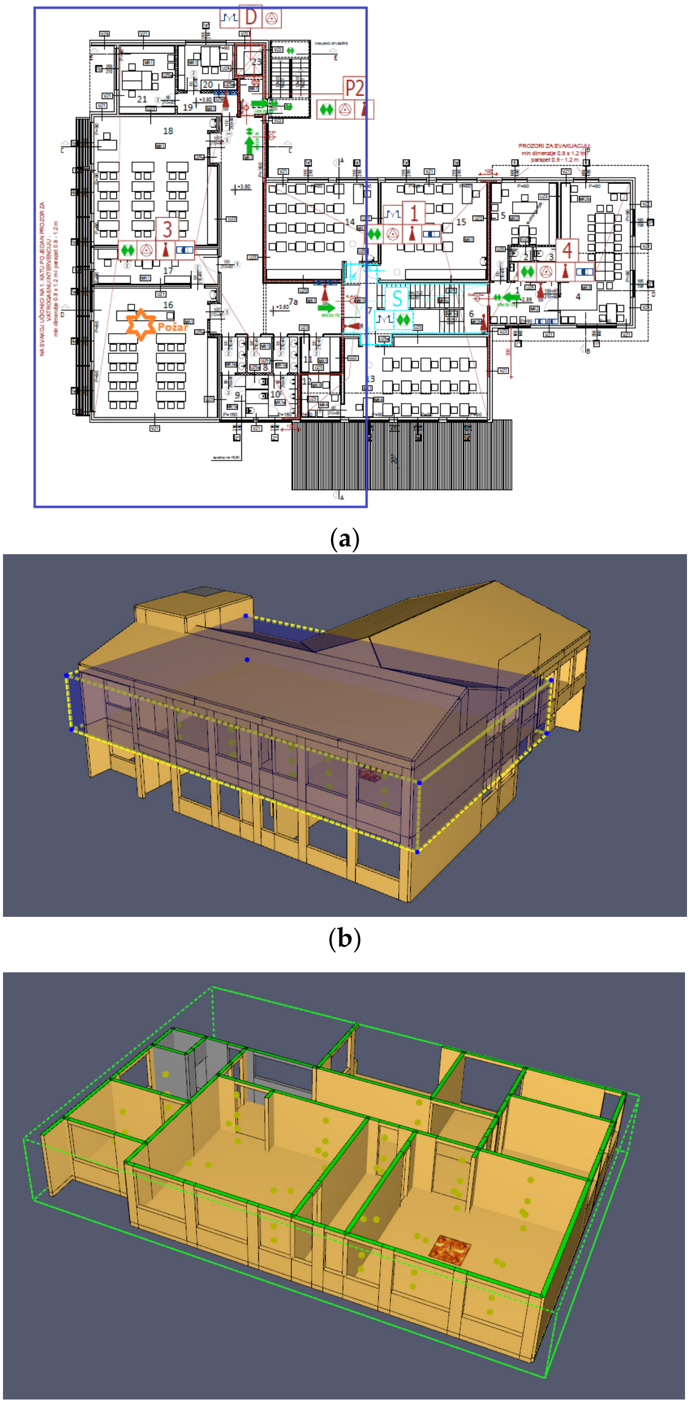
Based on the generated numerical mesh and the defined fire scenarios, the input data required to carry out the simulation was determined. The representativeness of the numerical results obtained is directly dependent on the quality and reality of the input parameters. For this reason, the input data are taken from reputable sources and the literature.

The flammability and heat released during the decomposition of wooden structures is determined by calorimetric measurements [37–39]. All internal partitioning structures are fabricated from 100 mm thick cross-laminated timber (CLT) panels. The external wall comprises 140 mm thick CLT panels, which are finished on the interior with plasterboard and on the exterior with a layer of mineral wool insulation topped with a thin coat of plaster. The internal load-bearing and fire-resistant partition walls are constructed from 140 mm thick CLT panels, with plasterboard cladding applied to both sides. The mezzanine floor is constructed using 200 mm thick CLT panels. Table 2 shows the physical properties of the building materials used in the model.

Table 2. List of layers of a load-bearing structure.

Structure	Layer	Thickness (mm)	Density (kg/m^3)	λ [W/mK]	Specific Heat (kJ/kgK)	Emissivity	The Class of Reaction HRN EN 13501-1 [40]
External wall	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2
	CLT	140	470	0.13	1.6	0.9	D
	Mineral wool	150	120	0.037	1.74	0.9	min A2
	Silicate plaster	3	1800	0.9	0.01	0.9	min A2
Internal wall—on the border of the fire compartment	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2
	CLT	140	470	0.13	1.6	0.9	D
	Mineral wool	100	120	0.037	1.74	0.9	min A2
	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2
Internal load-bearing wall	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2
	CLT	100	470	0.13	1.6	0.9	D
	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2
Mezzanine floor construction	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2
	Mineral wool	30	120	0.037	1.74	0.9	min A2
	CLT	200	470	0.13	1.6	0.9	D
	Gypsum—cardboard panels	2 × 12.5	750	0.25	1.06	0.9	min A2

The model considers a fire in a classroom that is part of the largest fire compartment (Figure 4). The methodology for fire design encompasses the identification of a fire scenario, the assessment of the fire's nature and intensity, the computation of temperature progression within the structural components, and the analysis of the mechanical response of the structure subjected to the fire conditions. Specifically, these scenarios reflect both typical and extreme conditions, which are crucial for understanding the potential variability in fire behaviour.



(**a**)

(**b**)

(**c**)

Figure 4. Fire location and selected fire sector: (**a**) floor plan, (**b**) 3D view, and (**c**) 3D view of the fire compartment.

3.5. Reactions

The formulation of an accurate response model is essential for acquiring dependable outcomes. This segment elucidates the methodology of establishing a response model, the justification for the selected model, and the ambiguities linked to its execution. Upon evaluating the state of the region, the varying values of the calorific value of timber are presented. While the work of Bartlett et al. [13,41,42] indicated a calorific value of 17.5 MJ/kg, Rinta-Paavola and Hostikka [43] proposed 13.75 MJ/kg. To reconcile these discrepancies and mitigate unfounded assumptions, this model incorporates two distinct reactions: CRIB pyrolysis and ELEMENT pyrolysis. The reactions pertaining to the wall and ceiling components are identical, whereas CRIB pyrolysis denotes a reactive entity introduced into the region via the "BURNER", which is allocated a heat combustion value of 17.5 MJ/kg, as per Bartlett et al. Conversely, for the ceilings and walls, a reactive substance generated from spruce material due to pyrolysis is designated with a heat of combustion value of 13.75 MJ/kg, as elucidated by Rinta-Paavola and Hostikka [43].

The combustion process is represented by a C3.4H6.2O2.5N0 reaction. The yield of soot and carbon monoxide was not provided in the research conducted by Rinta-Paavola and Hostikka [43]. Consequently, values of 0.015 for soot and 0.004 for carbon monoxide (g/g) were inferred based on the literature [44].

3.6. Fire Scenarios

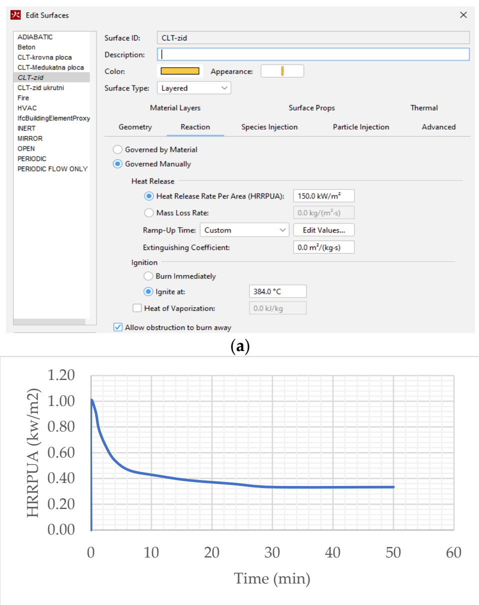
In the conducted simulation, a lit candle situated on the tabletop within the chamber was identified as the ignition source, leading to the table igniting, subsequently resulting in the conflagration of the entire edifice. In parametric fire simulations, we consider the ensuing conditions:

- The average density of the immobile fire load (CLT) is 1100 MJ/m^2.
- Oxygen is supplied via openings in the external walls.
- The simulation is carried out in 15 min (900 s), as firefighters' estimated arrival time from the fire department for an operation is 15 min.

In variant A, it is assumed that the CLT elements are unprotected/exposed and contribute to the development of the fire and the amount of heat released. It is not easy to determine the correct heat release. Calorimetric data are derived from experimental tests done by Lamande et al. [45].

After ignition, a peak value of HRR is observed; after which, there is a phase of deceleration until the phase of stagnation with a certain average value of HRR. In addition, different HRR values were determined for different heat flows. Nevertheless, a correlation can be observed between the peak value of HRR and the average value of HRR.

In Pyrosim [15], all CLT elements are defined to contribute to fire development after reaching a temperature of 384 °C (Figure 5a) when a certain amount of HRRPUA (heat release rate per unit area) is released, which is defined by the normalised HRRPUA curve (Figure 5b) based on previous experimental studies of CLT decomposition [45].



(**a**) (**b**)

Figure 5. CLT reaction: (**a**) HRRPUA and ignition temperature and (**b**) HRRPUA normalised.

Variant B: CLT elements that are protected by non-combustible plasterboard and therefore do not contribute to the development of a fire. The fire source was introduced with a BURNER spread over 2.25 m^2 of VENT in the centre of the classroom and specified with a HRRPUA curve and t^2 development for rapid fire (0.0469 kW/s^2). The maximum value of HRR is 5000 kW; therefore, the HRRPUA is 2222.22 kW/m^2, and the maximum developed power is reached after 327 s (Figure 6).

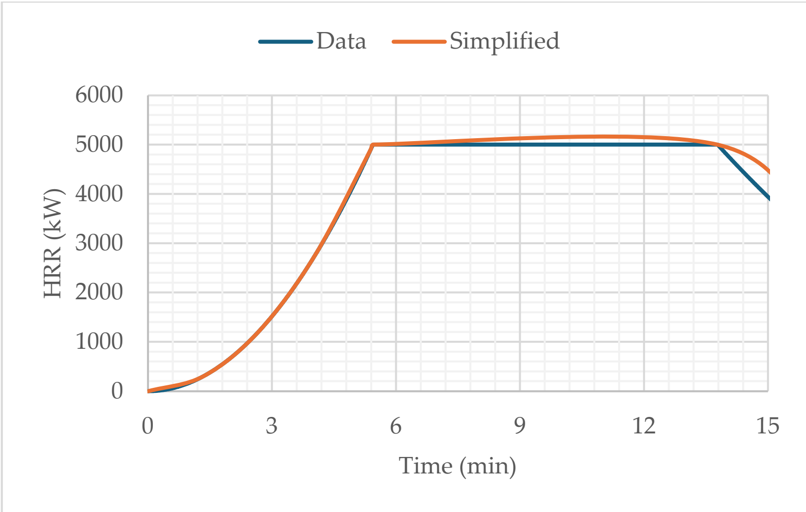


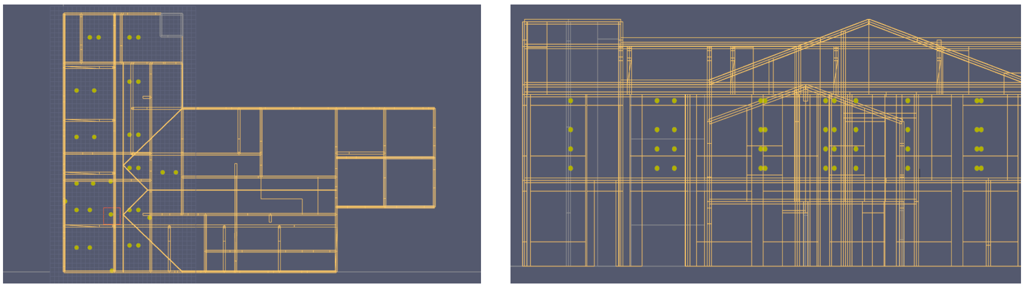
Figure 6. HRR diagram.

In order to ascertain that the burner faithfully emulates the fire, a simulation was conducted employing a mesh size of 10 cm, with all surfaces designated as inert boundary conditions. The primary emphasis of this investigation was exclusively on the thermal output arising from the combustion of the fire source, excluding the effects of other materials. The combustion heat has been established at 17.5 MJ/kg, as posited by Bartlett et al. [13].

3.7. Configuration of the Measuring Devices

In order to gather empirical data from simulations, measurement instruments (pertaining to both solid and gaseous phases) are strategically positioned within the designated area. The primary objective was to acquire information regarding the gas temperature, the amount of heat generated, the temperature variations on the surfaces of the CLT, and the resultant smoke production, specifically in terms of visibility. Consequently, the instruments are arranged at varying elevations above the ground and in proximity to the walls, as well as the floor and ceiling. Temperature is one of the most important parameters in fire scenarios, as it influences the structural integrity, material behaviour, and occupant safety. To measure temperature accurately in CFD analysis of fire in timber structures, we considered the following areas: near a fire source (to capture the maximum temperature gradients), at structural components (to assess thermal loading, which is critical for understanding timber degradation during a fire), vertical and horizontal stratification (to capture the temperature gradient in the fire compartment), avoiding direct heat interference (may be affected by localised heat sources), and finally, at representative locations, to understand the temperature distribution in the entire compartment. Similarly, to measure visibility effectively, the following was considered: smoke layer tracking (positioned at various heights to capture how the smoke layer evolves as it spreads across the space), near exits and escape routes (this ensures that data on smoke concentration and visibility along these critical pathways are captured), avoiding proximity to flame sources (placed at a safe distance from the fire to capture the actual smoke and particle distribution rather than heat distortion), and finally, strategic placement in the compartment layout, which is important in large timber structures where smoke movement can vary due to openings, vents, and architectural features.

Figure 7 illustrates the spatial configuration, and the horizontal distribution of the instruments affixed to the walls and ceiling, in addition to the apparatuses for monitoring gas temperature and visibility. The instruments designed for the gas phase are systematically dispersed throughout space and evaluate the ambient temperature at heights of 80, 160, 200, and 320 mm above the ground.



(**a**) (**b**)

Figure 7. Arrangement of measuring devices: (**a**) floor plan and (**b**) side view.

Instrumentation affixed to the components, positioned on both exposed and encapsulated surfaces within the chamber, recorded thermal readings at the surface and at multiple depths within the CLT elements. These instruments were strategically installed on the classroom walls, initially on the exposed surface and subsequently at an incremental depth of 20 mm, precisely aligned with the bond lines of the CLT.

3.8. Results

This section presents the results of the CFD simulations. First, the results are presented in terms of the developed heat release rate (HRR), the temperature of the gases, then that of the solid surfaces, and finally, the visibility. Subsequently, the simulation that is most suitable for comparison with experimental fire data in the CLT compartment is examined more in detail.

Figure 8 shows visualisations of gas temperature data obtained at intervals of every 100 s, where the development of the fire during a 15-min simulation is shown, for case A, when the CLT elements are exposed.

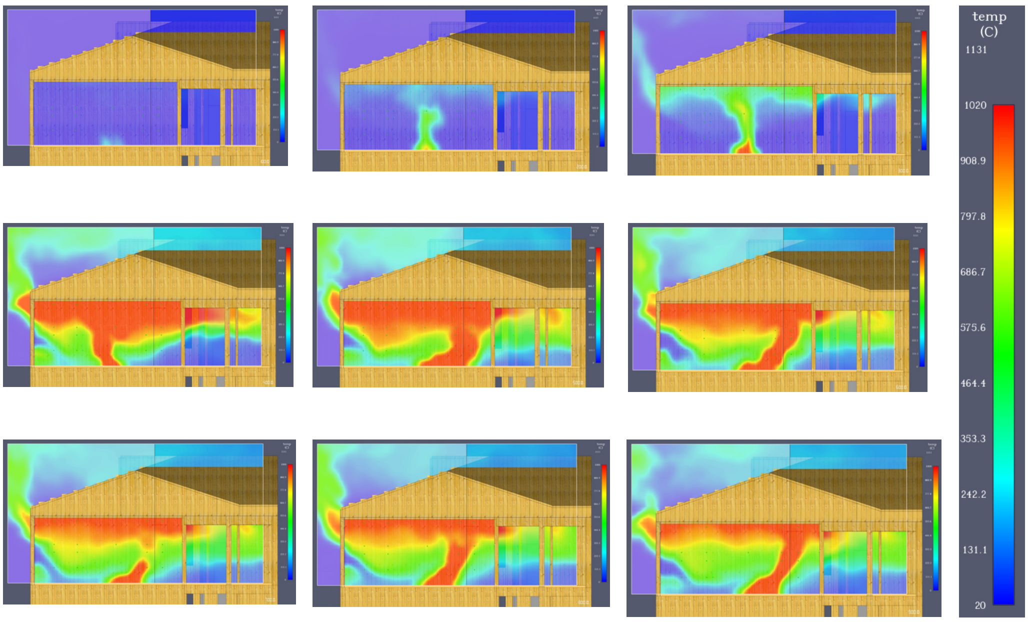


Figure 8. Temperature development (variant A)—time frame: every 100 s.

Figure 9 shows visualisations of the gas temperature data, which were determined at intervals of 100 s. It shows the development of the fire during a 15-min simulation for case B, when the CLT elements are protected.

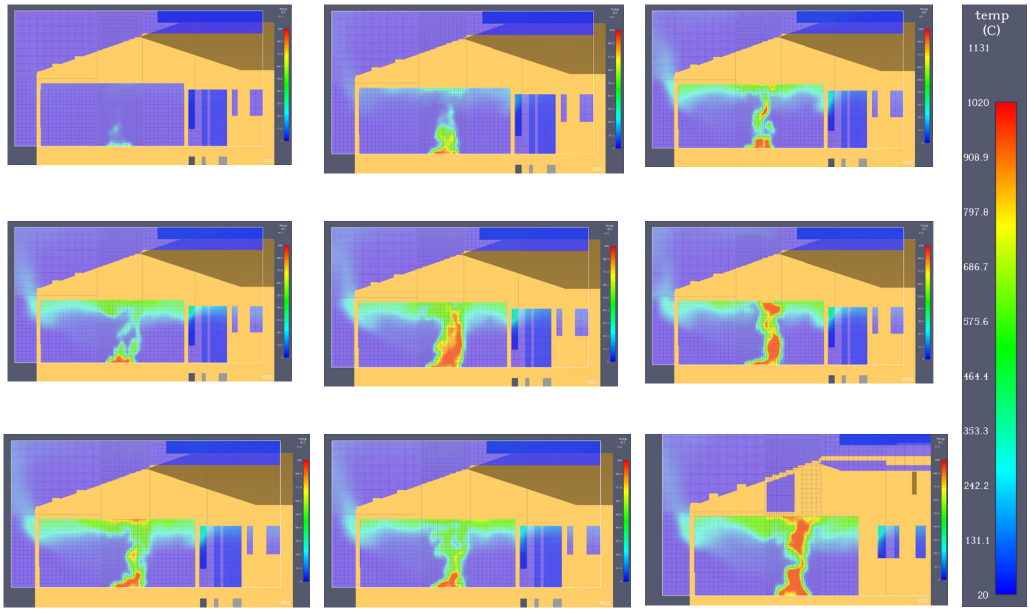


Figure 9. Temperature development (variant B)—time frame: every 100 s.

3.9. Heat Release Rate (HRR)

Figure 10 shows the moving average of the total HRR through the simulation for both cases.

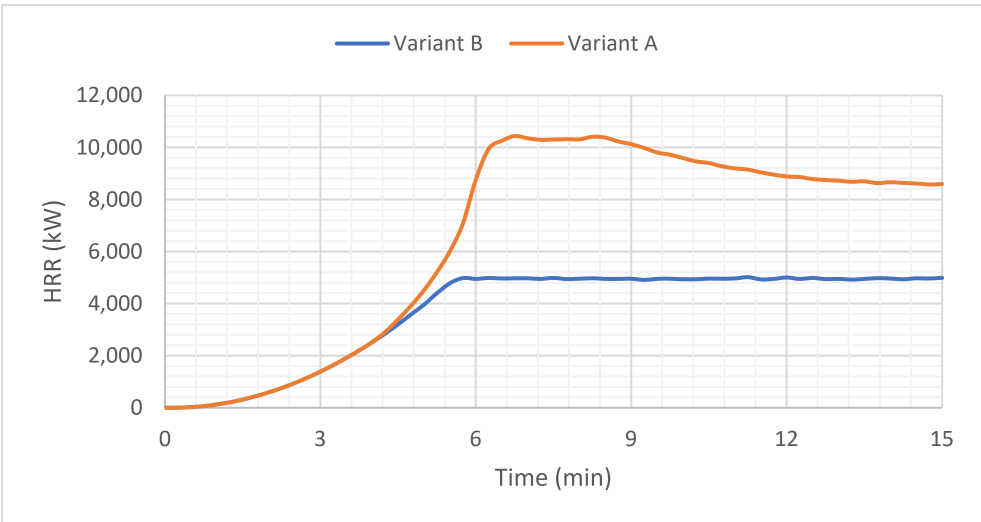


Figure 10. Comparison of HRR in the fire compartment of protected (B) and exposed (A) CLT.

The heat release rate (HRR) exhibits a progressive increase when the initial combustion event releases volatile compounds into the environment. The HRR escalates in accordance with the predetermined discharge of volatiles, demonstrating an average enhancement corresponding to the rapid combustion and attaining its zenith at 327 s (5.45 min—curve B). In the case of exposed cross-laminated timber (CLT) elements, a marked surge in HRR is observed post 250 s (4.17 min), escalating from 3000 kW to 10,000 kW within a period of 150 s (2.5 min). This apex is sustained for approximately 100 s, culminating in a maximum value of 10,410 kW. The peak HRR aligns with the initial fire achieving its projected maximum HRR of 5000 kW. Throughout this interval, the pyrolysates emitted from the wood surfaces contribute an additional 5000 kW to the HRR. Consequently, it can be inferred that up to 50% of the HRR is attributable to the supplementary fuel derived from the CLT, as can be seen in Figure 10, where the total HRR from the simulation is compared to the estimated HRR of the fire source.

The simulation reveals a decrease in HRR after 510 s (8.5 min). The deceleration rate is less steep compared to the initial growth rate that reached the peak. This level persisted until the simulation concluded, suggesting that the surfaces continued to release energy even after the fire was extinguished.

3.10. Gas Phase Temperature

Figure 11 shows the average temperature of the gases inside the classroom 200 cm above the floor level. In the simulation, the highest temperature in case B is reached about 360 (6.0 min) s or 450 s (7.5 min) after the outbreak of the fire. The temperature drop starts soon after reaching the maximum temperatures at a slowly decreasing rate. The experiment concluded after 15 min when the temperature decreased from its maximum to 418 °C, which is equivalent to 300 °C.

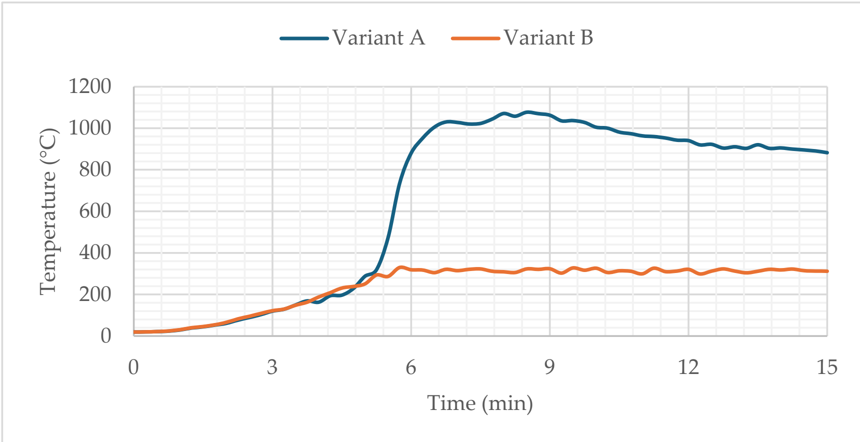


Figure 11. Average gas temperature 200 cm above the floor level.

Furthermore, the distribution of temperatures at a height of 1.6 m, in the entire fire compartment, is shown below. The arrangement of measuring devices can be seen below (Figure 12).

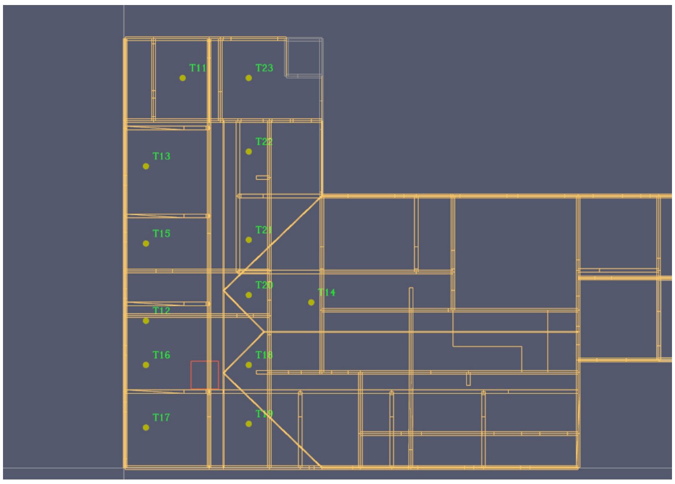


Figure 12. Arrangement of measuring devices at a height of 1.6 m above the floor.

The average gas temperatures within the classroom, measured at 160 cm above the floor, are depicted in Figure 13 for both scenarios. The simulation reveals that case A reaches its maximum temperature approximately 480 s (8.0 min) after ignition, while case B records its peak temperature of 75 °C at 510 s (8.5 min) post-ignition. Following these peak temperatures, a gradual decline in temperature begins. The simulation concludes after 15 min; at which point, the temperature has decreased from its highest point to an average of either 550 °C or 50 °C.

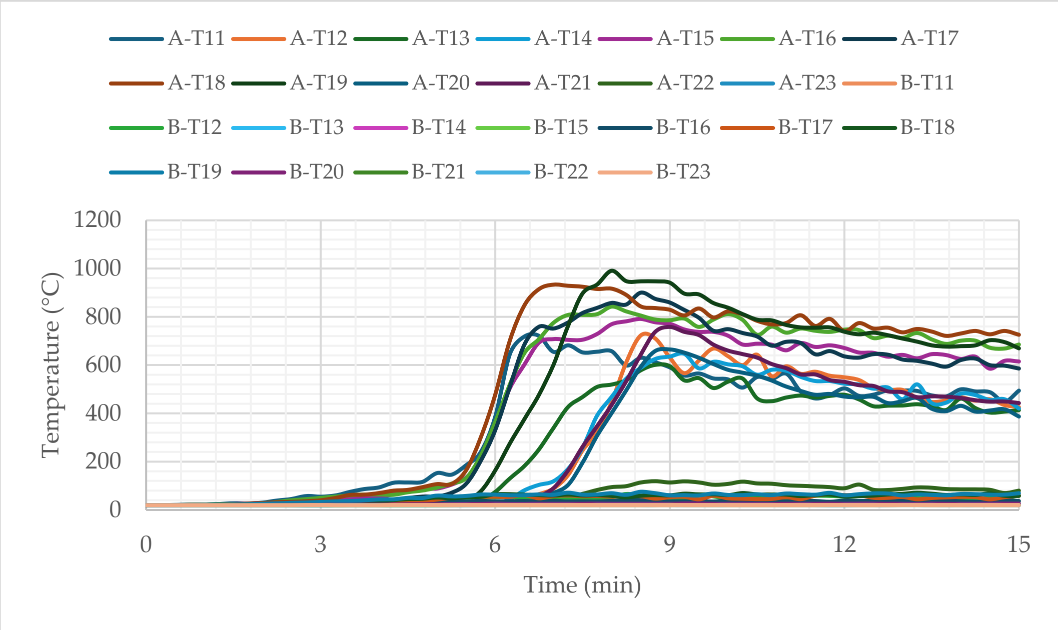
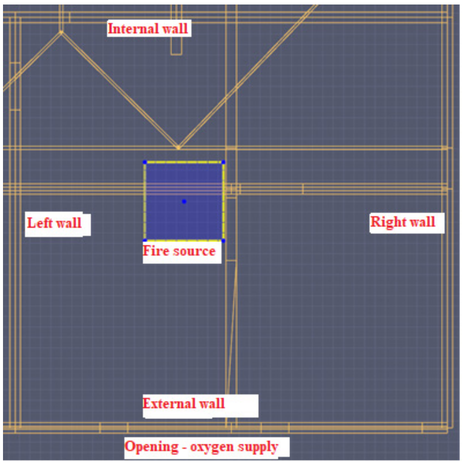


Figure 13. Temperatures in the fire compartment at a height of 1.6 m above the floor.

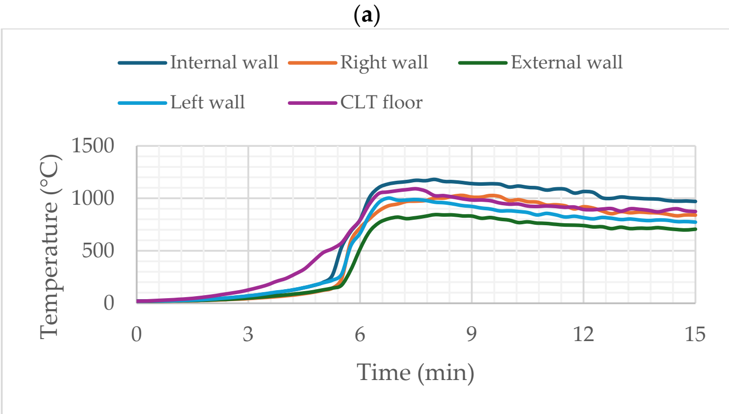
The thermal conditions of the gas phase significantly influence the carbonisation and structural characteristics of cross-laminated timber (CLT) when subjected to fire exposure. As the temperature of the gas escalates, the thermal degradation rate of the timber intensifies, resulting in an expedited and more profound carbonisation process [46]. Elevated temperatures facilitate the rapid decomposition of cellulose and hemicellulose components within the wood, thereby diminishing the mechanical properties of the material, including its strength and stiffness. This degradation phenomenon leads to a diminished load-bearing capacity of CLT, particularly in the surface layers that are in direct contact with the high-temperature gas. Furthermore, the extent of carbonisation, which is substantially governed by the gas temperature, also influences the overall structural integrity of the material, rendering it increasingly vulnerable to structural failure under applied loads [47]. In addition, heightened thermal conditions may induce internal stresses as a consequence of uneven thermal distribution, thereby further undermining the performance of CLT in fire-related scenarios. Temperatures of solids are discussed in more detail in the next paragraph.

3.11. Temperatures of Solid Bodies (CLT)

In this section, the temperature on the surface of the CLT bounding the classroom where the fire initiated is analysed. Depending on the position of the wall in relation to the fire source and the ventilation (Figure 14a), the difference in the developed temperatures is visible (Figure 14b).



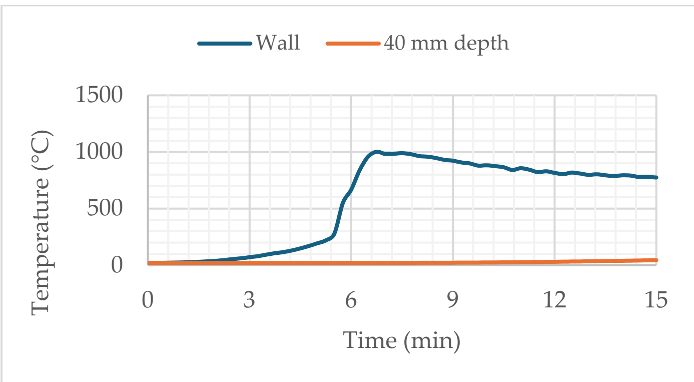
(**a**)



(**b**)

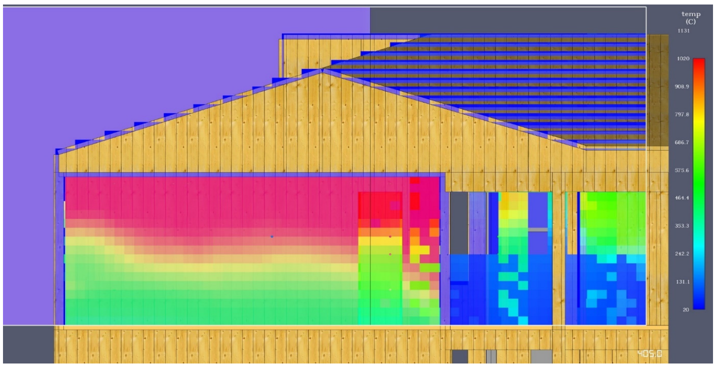
Figure 14. Temperatures of sold bodies—CLT: (**a**) arrangement of CLT elements; (**b**) solid-phase temperatures.

The average temperatures for various thicknesses (variant A) of the exposed walls and ceiling are depicted in Figure 15. As the compartment heats up, the exposed surface's measured temperature shows a swift increase. Temperature readings at a depth of 40 mm in the first layer of both the wall and ceiling demonstrate a minimal temperature rise, leading to the exclusion of deeper temperature measurements from the analysis. The wall surface attains an average peak of 1000 °C in approximately 405 s (6.75 min), while the ceiling surface reaches 1090 °C in about 450 s (7.5 min). A continued decrease in temperature is anticipated towards the conclusion, aligning with the declining heat release rate (HRR).

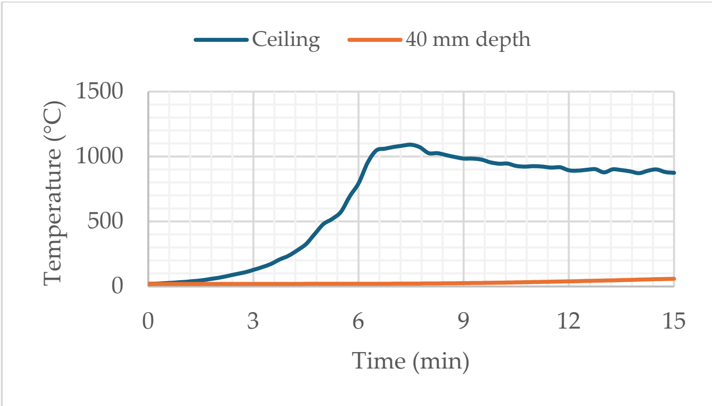


(**a**)

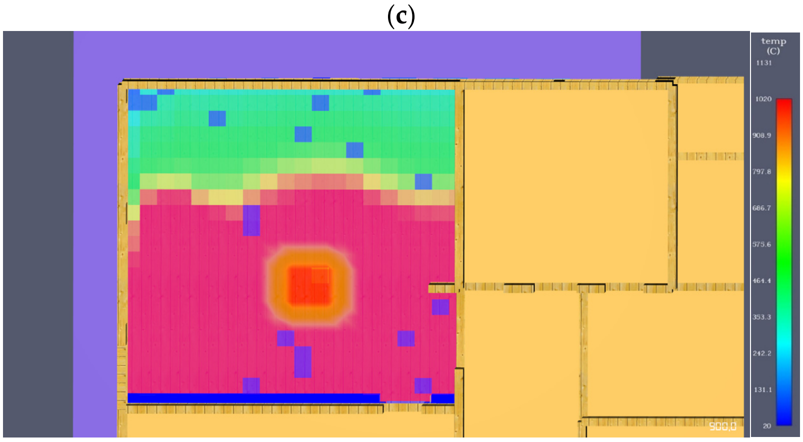
Figure 15. *Cont.*



(**b**)



(**c**)



(**d**)

Figure 15. Temperatures of exposed CLT: (**a**) temperature development of the wall at a depth of 40 mm; (**b**) wall temperature; (**c**) temperature development of the ceiling at a depth of 40 mm; (**d**) ceiling temperature.

3.12. Visibility

Concerning investigations into smoke generation in CLT structures, numerous research initiatives have explored the influence of combustible materials on fire dynamics. For example, empirical studies have demonstrated that timber, inclusive of CLT, yields a greater volume of smoke in comparison to non-combustible substances. A research endeavour conducted by Boe et al. [48,49] scrutinised fire dynamics within CLT frameworks and underscored the impact of timber combustion on smoke proliferation. Likewise, the investigation by Cheng et al. [50] assessed the propagation of smoke in timber constructions, observing that timber can exacerbate smoke production during fire events. These investigations imply that the elevated quantities of smoke generated in such edifices can significantly diminish visibility, thereby complicating evacuation protocols.

As part of this research, the main results related to smoke production and visibility are presented below. Figure 16 shows the development of soot (variant A, exposed to CLT) at certain time intervals. The results are presented in a 3D view and a view of the soot density at a height of 2 m above the ground. The results are shown after 100 (1.67 min), 400 (6.67 min), and 900 s (15 min). Visibility was initially considerably reduced, especially in the classroom where the fire had broken out, to an average of 20 m, while, in the adjacent rooms, it averaged 30 m. After 320 s, the smoke spread to the neighbouring rooms, and after 400 s, the visibility in the classroom was less than 2 m and, in the neighbouring rooms, 5 m on average. Finally, after 900 s (15 min), the smoke spread throughout the entire fire compartment, and visibility was considerably reduced.

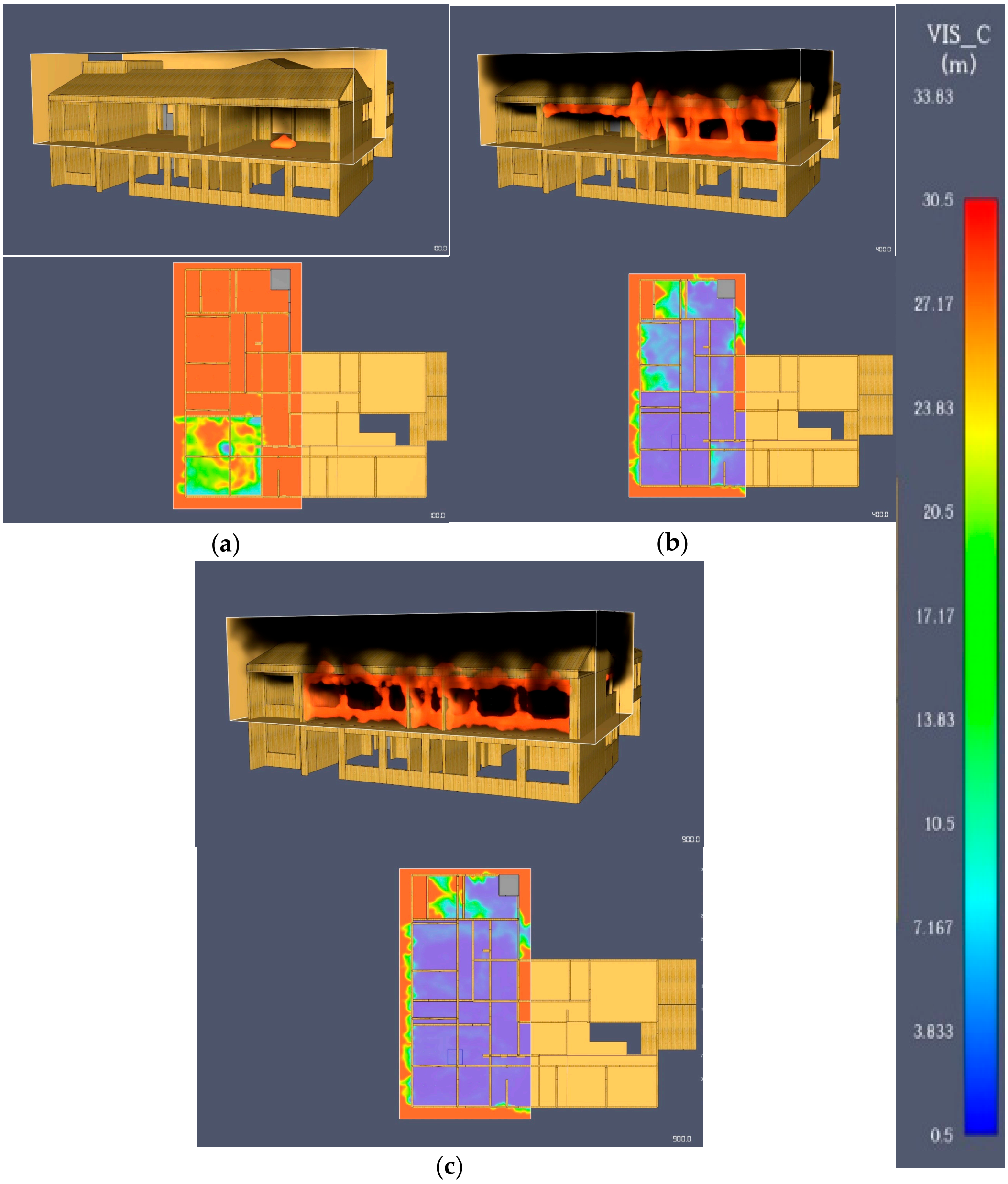


Figure 16. Visibility and soot density—variant A: (**a**) after 100 s, (**b**) after 400 s, and (**c**) after 900 s.

Figure 17 shows the development of the soot (variant B, protected by CLT) in certain time intervals. The display consists of a 3D representation and a display of the soot density at a height of 2 m above the ground. The results are displayed after 100 (1.67 min), 400 (6.67 min), and 900 s (15 min). Visibility is significantly reduced, especially in the classroom where the fire broke out, to an average value of 6 m, while, in the neighbouring rooms, it averages 15 m.

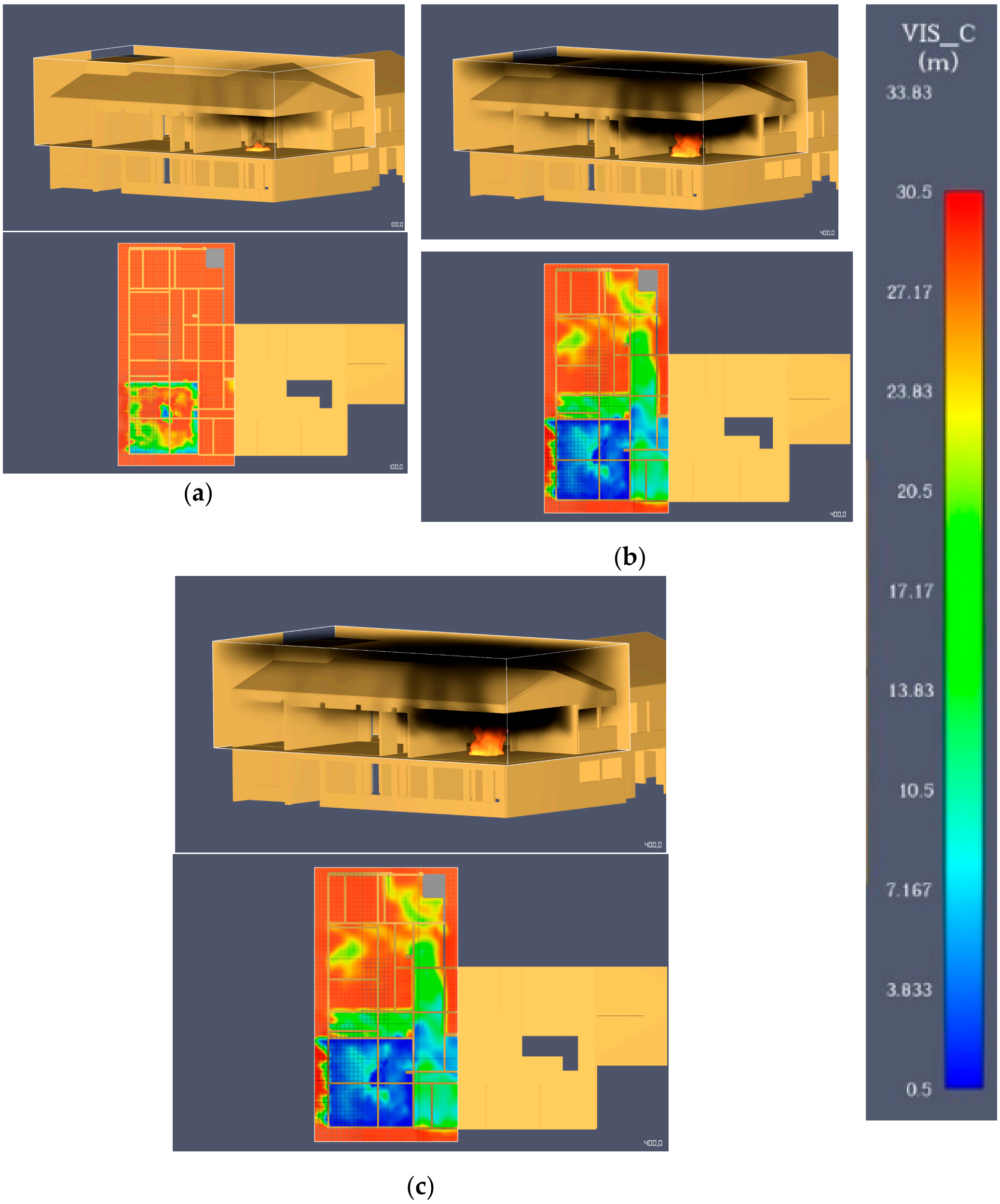
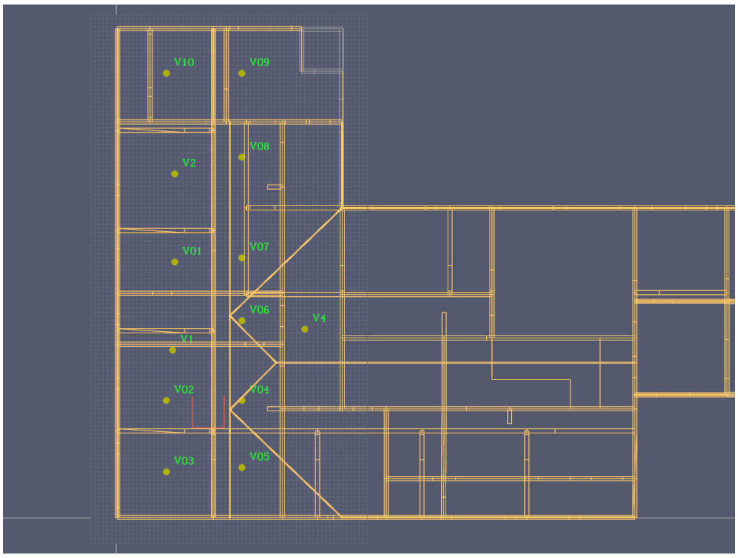
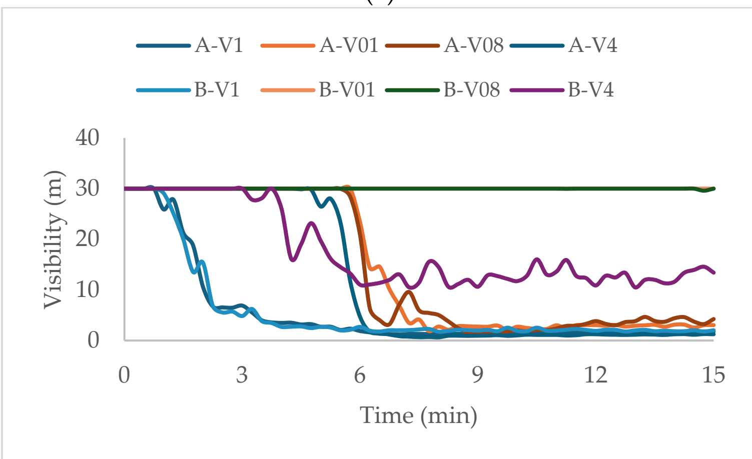


Figure 17. Visibility and density of soot—variant B: (**a**) after 100 s, (**b**) after 400 s, and (**c**) after 900 s.

It can be concluded that the exposure of CLT contributes to the reduction of visibility and dispersion of the smoke itself, which is due to the ignition of the material. In variant A (exposed CLT), the smoke spread more in the room itself, while, in variant B, it was more concentrated in the classroom itself, where the fire broke out. The arrangement of the visibility meters is shown in Figure 18a, while Figure 18b shows a comparison of the visibility for both fire scenarios at characteristic positions within the classroom and in adjacent rooms.



(**a**)



(**b**)

Figure 18. Visibility inside the fire compartment: (**a**) arrangement of devices and (**b**) visibility inside the fire compartment.

4. Discussion

The notion that wooden structures are more susceptible to fire is outdated. When properly designed, constructed, and compliant with relevant regulations, timber buildings are no more vulnerable to fire than other construction types. For cross-laminated timber (CLT) structures with numerous exposed timber surfaces, it is essential to consider the increased fire load and CLT's charring characteristics. In tall buildings, most of the CLT timber should be protected from ignition to prevent long-lasting, difficult-to-extinguish fires.

Fire dynamics in compartments with exposed timber surfaces differ significantly from those with non-combustible cladding. The key differences include:

- elevated heat release rates
- quicker flashover
- higher gas and solid temperatures
- increased smoke production
- extended cooling phase with higher temperatures

Unlike rooms with non-combustible linings, those with exposed wooden surfaces can sustain combustion even after all interior combustible materials have burned. The exposed wood will continue to burn if sufficient heat is transferred to the pyrolysis area within the CLT elements. During the cooling phase, heat transfer typically occurs through convection from the burning surface and radiation from adjacent exposed wood surfaces on ceilings and walls. Sufficient heat exchange between exposed surfaces can prolong the fully developed fire stage.

However, CLT panels have inherent fire resistance and can contribute to the fire safety strategy in buildings. The need for additional protection in the form of plasterboard cladding will depend on the thickness of the board and the fire protection measures required. It is important that regulations recognise and make a distinction between CLT and light timber frame construction where fire protection is provided by fire-resistant cladding. In this case, this is necessary, because timber elements such as frames, beams, or rafters usually have smaller cross-sections that ignite and burn relatively quickly when exposed to fire if they are not protected. The reason for this is the ratio of surface area to volume. However, CLT elements are more robust elements where, if a charred layer forms, the load-bearing capacity of the remaining timber is estimated by calculating the required fire resistance. CLT elements can be dimensioned to provide sufficient fire resistance, and for many smaller one- or two-storey buildings, CLT elements can be used without fire protection. In multi-storey buildings, however, CLT is usually protected.

In addition, physically based fires are more general in nature than the standardised time–temperature fire curve, which was developed as a benchmark and is commonly used for fire resistance testing and classification of building components. When (structural) timber surfaces in a fire compartment are exposed to fire, they contribute to the fire dynamics. Consequently, structural wood elements can influence the growth, duration, maximum temperature, and cooling phase, including the probability of combustion (self-extinguishing). Therefore, depending on the amount of exposed structural elements, the additional heat release should be considered. Methods of analysis are proposed for the dimensioning of timber structures exposed to physically induced fires. According to the guidelines prEN 1995-1-2 [51], which are confirmed in this paper, the combustion of timber structures can be analysed considering the contribution of the fire load of the structure to the total fire load. This opens up new possibilities for designing the fire resistance of large and tall timber buildings for a wide range of fire scenarios.

The findings are evaluated to determine the necessary fire protection level and implement appropriate measures. Additionally, this section explores potential model limitations and proposes enhancements. The primary questions addressed in the CFD analysis are:

1. How accurate is the model?
2. What constraints does the model have?
3. How can future models be enhanced for more precise results?
4. Can they be applied in real-world scenarios?

When comparing the simulation to existing research [52–55], several factors were identified that might cause result discrepancies. The model's early prediction of CLT ignition torque could be influenced by various elements. The proposed model's input parameters may be overly reactive during the initial conditions, causing an accelerated response to heat input. The moisture content, which was not included in the simulation, might also contribute to this effect. Moreover, a slight deviation was noted in the HRR curve after reaching its peak value, potentially due to the fire's complex dynamics and the simulation model's limitations in representing the fire within the façade domain. This suggests that expanding the domain could allow for additional combustion.

Additionally, conducting a mesh sensitivity analysis would be valuable for pinpointing specific issues. Should the simulation fail to accurately depict the quantity of pyrolysis gases generated, it would impact the heat release rate (HRR). However, such an analysis would demand considerable time and computational resources, which is why it was not undertaken in this research.

Moreover, the accuracy of the gas temperature predictions directly influences the heat transfer to cross-laminated timber (CLT) elements, consequently affecting the temperatures in all CLT layers not directly exposed to fire. Temperature governs the pyrolysis processes that determine the pyrolysate mass flow from CLT surfaces. It is believed that properly defining ventilation conditions significantly impacts the resulting temperatures, necessitating more comprehensive studies on various ventilation scenarios. In situations where a larger amount of fuel (CLT) is available and oxygen supply is restricted, discrepancies in char height estimation (overestimation) may occur compared to experimental findings, ultimately affecting the predicted fire resistance of CLT.

While computational fluid dynamics (CFD) provides significant insights into combustion phenomena, the dependability of the outcomes is profoundly contingent upon precise input data and the hypotheses established in the simulation process. It is imperative to acknowledge that CFD simulations are only as robust as the data upon which they are predicated, and variances between anticipated and actual results may emerge due to ambiguities in the model parameters, boundary conditions, and environmental influences. Consequently, the necessity for additional empirical investigations to corroborate CFD forecasts becomes increasingly evident. Therefore, the potential improvement involves incorporating more detailed empirical data on fire behaviour, fuel properties, and environmental factors, allowing for better calibration of the model. Additionally, integrating machine learning techniques or hybrid models could help refine the predictions by learning from large datasets of fire experiments or real-world fire events.

Moreover, while CFD presents considerable potential in forecasting fire dynamics, it is accompanied by considerable expenditures associated with both software procurement and computational capabilities. The intricacy of simulations, particularly for expansive or intricate fire scenarios, necessitates high-performance computing, which can incur significant costs. These elements must be meticulously evaluated when contemplating the application of CFD for extensive implementations, especially in relation to fire safety. Ultimately, the findings observed in this investigation could contribute to fire safety legislation concerning timber structures. Fire safety regulations must evolve in response to the escalating utilisation of materials such as timber, where combustion behaviour may diverge from that of conventional construction substances. The knowledge acquired from CFD simulations could facilitate the development of safer design methodologies, enhance fire risk evaluations, and potentially lead to revised safety codes and standards. By integrating CFD forecasts into fire safety legislation, regulatory bodies could establish more precise and data-informed regulations to safeguard human life and property while fostering innovation in construction materials.

Nevertheless, it is crucial to acknowledge that, despite certain uncertainties, the model demonstrates promising results regarding the developed thermal performance and combustion model of CLT, which is a key concern for the next generation of EN 1995-1-2 [51]. This observation is encouraging and indicates that the Fire Dynamics Simulator (FDS) has the potential to accurately replicate fire scenarios if the input parameters are carefully considered and calibrated. The ultimate goal is for these models to be deemed suitable for practical application in designing fire safety measures.

5. Conclusions

In the performance-based design of timber structures under fire conditions, the contribution of combustible materials changes the dynamics of the fire. The intensity and duration of the fire are decisive factors in planning and should be correctly assessed. Advanced numerical simulations were used to evaluate the performance of the CLT building under fire conditions. The results were further confirmed by comparison with previous experimental data.

One of the objectives of this work was to evaluate the accuracy of the model and the possibility and justification of using FDS simulations in practice. Another objective of the work was to compare the fire dynamics in the compartment, in conditions when the CLT structure is exposed or protected, and finally, to dimension the CLT structure according to the applicable standard. Based on the CFD simulation results, the following conclusions were drawn:

- CFD analysis proved to be effective for the simulation of fire dynamics in compartments with structural elements made of wood (CLT).
- The advanced simulation showed promising results in terms of the parameters of the developed HRR, the temperatures of gases and solids, and the visibility due to smoke development. The HRR was a parameter that showed satisfactory accuracy compared to previous studies and simulations. CLT contributes significantly to the total HRR released.
- The predicted temperatures of gases and solids agree that they served as a basis for the dimensioning of CLT but can also serve as a basis for the design of fire protection measures, which are not part of this work.
- The current EN 1995-1-2 is not conservative regarding the temperatures that develop within the fire compartment with exposed timber surfaces. Therefore, an increase in the zero-strength layer should be considered in the new generation of EN, and PBD designs with clear guidelines should be introduced.
- The combustion of timber and the charring rate determined by advanced simulations (Pyrosim) confirmed the recommendations in prEN 1995-1-2:2025.
- The simulations showed that the smoke develops more in the fire compartment when the wood structure is exposed. In the case where the CLT is protected, visibility is restricted mainly in the classroom where the fire broke out, while, in the case of the exposed CLT, visibility is restricted in almost the entire fire compartment.

The second research question aimed to determine the limitations, and the following conclusions were reached:

- The temperature of the gaseous phase is a critical parameter that affects many aspects of fire compartments. Therefore, a more detailed investigation of the chosen values for the heat of combustion of CLT is required.
- The fact that the model is not able to account for the additional heat generated by the smouldering combustion of wood is seen as a limitation in obtaining more accurate results. This type of combustion is not included in the simulation despite its potential impact on HRR and gas phase temperature.
- Time for calculations and running simulations. This lengthy process limits the flexibility of the research and slows down the generation of results, making it difficult to assess the influence of different parameters on the simulation results and to validate the model itself. Due to the complexity in fire dynamics, simulations require substantial computational power, especially when considering high-resolution spatial mesh or long-duration simulations. In our study, we had to optimise the model to balance computational feasibility and accuracy, which can introduce some level of approximation, particularly in capturing intricate interactions or rare events in fire behaviour.

It is essential that future research builds upon the results of this study through real-world testing and data collection, as empirical validation is key to ensuring the reliability and accuracy of CFD predictions in fire scenarios.

Finally, it is important to emphasise that the intervention time provided for the firefighters should be respected in any case, because exceeding the specified time leads to an increase in the heat load of the building, i.e., the heat output of the fire. In the simulation, the time exposed to fire is significantly lower than the minimum required fire resistance under standard use conditions, and for both fire scenarios, we can conclude that the selected fire intensity in the given time (15 min) does not significantly reduce the mechanical properties of CLT.

Author Contributions: Conceptualisation, N.P., D.S., and V.R.; methodology, N.P. and D.S.; software, N.P.; validation, N.P. and D.S.; formal analysis, N.P.; investigation, N.P.; resources, V.R.; data curation, N.P.; writing—original draft preparation, N.P.; writing—review and editing, N.P., D.S., and V.R.; visualisation, N.P.; supervision, D.S.; project administration, V.R.; funding acquisition, V.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The project documentation is the property of the Ivan Goran Kovačić Elementary School in Gora, Petrinja, created by the company Planetaris d.o.o., for which permission for use was obtained.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Harte, A.M. Mass Timber—The Emergence of a Modern Construction Material. *J. Struct. Integr. Maint.* **2017**, *2*, 121–132. [CrossRef]
2. Jeleč, M.; Varevac, D.; Rajčić, V. Križno Lamelirano Drvo (CLT)-Pregled Stanja Područja. *Gradjevinar* **2018**, *70*, 75–95.
3. Brandon, D.; Dagenais, C. *Fire Safety Challenges of Tall Wood Buildings-Phase 2: Task 5-Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire*; Final Report; NFPA: Quincy, MA, USA, 2018.
4. Muszyński, L.; Gupta, R.; Hong, S.h.; Osborn, N.; Pickett, B. Fire Resistance of Unprotected Cross-Laminated Timber (CLT) Floor Assemblies Produced in the USA. *Fire Saf. J.* **2019**, *107*, 126–136. [CrossRef]
5. Frangi, A.; Fontana, M.; Hugi, E.; Jübstl, R. Experimental Analysis of Cross-Laminated Timber Panels in Fire. *Fire Saf. J.* **2009**, *44*, 1078–1087. [CrossRef]
6. Buchanan, A.H.; Kwabena Abu, A. *Structural Design for Fire Safety*; John Wiley and Sons: Hoboken, NJ, USA, 2017.
7. Östman, B.; Brandon, D.; Frantzich, H. Fire Safety Engineering in Timber Buildings. *Fire Saf. J.* **2017**, *91*, 11–20. [CrossRef]
8. Hopkin, D.; Węgrzyński, W.; Gorska, C.; Spearpoint, M.; Bielawski, J.; Krenn, H.; Sleik, T.; Blondeau, R.; Stapf, G. Full-Scale Fire Experiments on Cross-Laminated Timber Residential Enclosures Featuring Different Lining Protection Configurations. *Fire Technol.* **2024**, *60*, 3771–3803. [CrossRef]
9. Vairo, M.; Pignatta Silva, V.; Hideyoshi Icimoto, F. Behavior of Cross-Laminated Timber Panels during and after an ISO-Fire: An Experimental Analysis. *Results Eng.* **2023**, *17*, 100878. [CrossRef]
10. Mcgregor, C.J. Contribution of Cross Laminated Timber Panels to Room Fires. Master's Thesis, Carleton University, Ottawa, ON, Canada, 2013.
11. Jakobsen, A.; Morten Birk Sabroe Valkvist, A.; Safety Jens Christian Bennetsen, N.; Rolf Ehlert Carstensen, R.; Gustav Lanng Madsen, C.; Kim Sommerlund-Thorsen, C.; Carsten Strüwing Hansen, D.; Brandvaesen Hovedstadens Beredskab Sune Nygaard, F.; Bro Lars Schiøtt Sørensen, C.; Norske Veritas, D. CFD Best Practice Deltagende Parter. Available online: https://hbr.dk/wp-content/uploads/2016/10/Best-Practice-CFD-november-2009.pdf (accessed on 2 October 2024).
12. Boverket. BFS 2011:27 Boverkets Allmänna Råd Om Analytisk Dimensionering Av Byggnaders Brandskydd, BBRAD. 2011. Available online: https://www.boverket.se/Resources/constitutiontextstore/BBRAD/PDF/Konsoliderad_BBRAD_BFS_2011-27.pdf (accessed on 2 October 2024).
13. Bartlett, A.; Hadden, R.M.; Bisby, L.A.; Law, A. Analysis of Cross-Laminated Timber Charring Rates upon Exposure to Non-standard Heating Conditions. In Proceedings of the 14th International Conference and Exhibition on Fire and Materials 2015, San Francisco, CA, USA, 2–4 February 2015; pp. 667–681.
14. Rein, G.; Bar-Ilan, A.; Fernandez-Pello, A.C.; Alvares, N. A Comparison of Three Models for the Simulation of Accidental Fires. *J. Fire Prot. Eng.* **2006**, *16*, 183–209. [CrossRef]
15. Thunderhead Engineering. PyroSim. Available online: https://www.thunderheadeng.com/pyrosim/ (accessed on 22 April 2024).
16. Korhonen, T.; Hostikka, S. *Fire Dynamics Simulator with Evacuation: FDS+Evac, Technical Reference and User's Guide (FDS 5.5.0, Evac 2.2.1). Technical Reference and User's Guide*; VTT Technical Research Centre of Finland: Otakaari, Finland, 2010.
17. Osvaldová, L.M.; Gašpercová, S. The Evaluation of Flammability Properties Regarding Testing Methods. *Civ. Environ. Eng.* **2015**, *11*, 142–146. [CrossRef]
18. Olenick, S.M.; Carpenter, D.J. An Updated International Survey of Computer Models for Fire and Smoke. *J. Fire Prot. Eng.* **2003**, *13*, 87–110. [CrossRef]
19. Jancík, J.; Magdolenová, P.; Markert, F. Comparison of Cone Calorimetry and FDS Model of Low-Density Fiberboard Pyrolysis. In Proceedings of the 9th International Conference on Wood & Fire Safety 2020, Strbske Pleso, Slovakia, 3–6 May 2020; pp. 144–151.
20. Alvares, N.; Fernandez-Pello, A.C. Fire Initiation and Spread in Overloaded Communication System Cable Trays. *Exp. Therm. Fluid Sci.* **2000**, *21*, 51–57. [CrossRef]
21. Cox, G.; Kumar, S. Field Modelling of Fire in Forced Ventilated Enclosures. *Combust. Sci. Technol.* **1987**, *52*, 7–23. [CrossRef]
22. Björkman, J.; Keski-Rahkonen, O. *Simulation of the Steckler Room Fire Experiment by Using SOFIE CFD-Model*; VTT Technical Research Centre of Finland: Otakaari, Finland, 1996.
23. Tabaczenski, R.; Corrêa, C.; Pires, T.A.; Rêgo e Silva, J.J. Simulação Numérica e Experimento de Incêndio em Dormitório Residencial. *Revista ALCONPAT* **2018**, *9*, 15–29. [CrossRef]

24. Li, S.; Jiaolei, Z.; Zhao, D.; Deng, L. Study on Fire Resistance of a Prefabricated Reinforced Concrete Frame Structure. *J. Struct. Fire Eng.* **2021**, *12*, 363–376. [CrossRef]
25. *EN 1995-1-2:2004/A2:2014*; Eurocode 5: Design of Timber Structures—Part 1–2: General-Structural Fire Design. CEN: Brussels, Belgium, 2014. Available online: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1995.1.2.2004.pdf (accessed on 27 June 2022).
26. Van Coile, R.; Lucherini, A.; Chaudhary, R.K.; Ni, S.; Unobe, D.; Gernay, T. Cost-Benefit Analysis in Fire Safety Engineering: State-of-the-Art and Reference Methodology. *Saf. Sci.* **2023**, *168*, 106326. [CrossRef]
27. *ISO 834-10:2014*; Fire Resistance Tests—Elements of Building Construction: International Technical Standard. ISO: Geneva, Switzerland, 2014.
28. Narodne Novine. Zakon o Gradnji (NN 153/13, 20/17, 39/19, 125/19). 2019. Available online: https://www.zakon.hr/z/690/Zakon-o-gradnji (accessed on 22 April 2024).
29. Narodne Novine. Zakon o Zaštiti od Požara (NN 92/10, 114/22). 2023. Available online: https://www.zakon.hr/z/349/Zakon-o-za%C5%A1titi-od-po%C5%BEara (accessed on 22 April 2024).
30. Pravilnik o Otpornosti na Požar i Drugim Zahtjevima Koje Građevine Moraju Zadovoljiti u Slučaju Požara. Available online: https://narodne-novine.nn.hr/clanci/sluzbeni/2013_03_29_505.html (accessed on 27 June 2022).
31. *Guidelines of the Austrian Institute of Construction Engineering (OIB) OIB Guideline 6 Energy Conservation and Thermal Protection Long-Term Renovation Strategy*; OIB: Vienna, Austria, 2020; Available online: https://www.oib.or.at/sites/default/files/oib-ltrs_en.pdf (accessed on 10 October 2024).
32. *NFPA 101: Life Safety Code*; NFPA: Quincy, MA, USA, 2024.
33. Jelčić Rukavina, M.; Carević, M.; Banjad Pečur, I. *Zaštita Pročelja Zgrada Od Požara-Priručnik Za Projektiranje i Izvođenje*; Sveučilište u Zagrebu, Građevinski Fakultet: Zagreb, Croatia, 2017.
34. Richter, F.; Rein, G. A Multiscale Model of Wood Pyrolysis in Fire to Study the Roles of Chemistry and Heat Transfer at the Mesoscale. *Combust. Flame* **2020**, *216*, 316–325. [CrossRef]
35. Sun, Q.; Turkan, Y.; Fischer, E. Develop and Benchmark FDS Numerical Models to Simulate Fundamental Fire Behavior in CLT Structures. In Proceedings of the International Symposium on Automation and Robotics in Construction, Waterloo, ON, Canada; 2021; pp. 319–326.
36. Liu, J.; Fischer, E.C. Review of Large-Scale CLT Compartment Fire Tests. *Constr. Build. Mater.* **2022**, *318*, 126099. [CrossRef]
37. Tran, H.C.; White, R.H. Burning Rate of Solid Wood Measured in a Heat Release Rate Calorimeter. *Fire Mater.* **1992**, *16*, 197–206. [CrossRef]
38. Wiesner, F.; Bisby, L.A.; Bartlett, A.I.; Hidalgo, J.P.; Santamaria, S.; Deeny, S.; Hadden, R.M. Structural Capacity in Fire of Laminated Timber Elements in Compartments with Exposed Timber Surfaces. *Eng. Struct.* **2019**, *179*, 284–295. [CrossRef]
39. Wade, C.A. A Theoretical Model of Fully Developed Fire in Mass Timber Enclosures. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand, 2019.
40. *HRN EN 13501-1:2019*; Fire Classification of Construction Products and Building Elements—Part 1: Classification Using Data from Reaction to Fire Tests. Croatian Standards Institute: Zagreb, Croatia, 2019.
41. Hadden, R.M.; Bartlett, A.I.; Hidalgo, J.P.; Santamaria, S.; Wiesner, F.; Bisby, L.A.; Deeny, S.; Lane, B. Effects of Exposed Cross Laminated Timber on Compartment Fire Dynamics. *Fire Saf. J.* **2017**, *91*, 480–489. [CrossRef]
42. Bartlett, A.I.; Hadden, R.M.; Hidalgo, J.P.; Santamaria, S.; Wiesner, F.; Bisby, L.A.; Deeny, S.; Lane, B. Auto-Extinction of Engineered Timber: Application to Compartment Fires with Exposed Timber Surfaces. *Fire Saf. J.* **2017**, *91*, 407–413. [CrossRef]
43. Rinta-Paavola, A.; Hostikka, S. A Model for the Pyrolysis of Two Nordic Structural Timbers. *Fire Mater.* **2022**, *46*, 55–68. [CrossRef]
44. Norén, J.; Rosberg, D. Developing a Swedish Best Practice Guideline for Proper Use of Cfd-Models When Performing Aset-Analysis. In Proceedings of the Fire and Evacuation Modeling Technical Conference (FEMTC) 2014, Gaithersburg, MD, USA, 8–10 September 2014.
45. Lamandé, A.; Marchetti, V.; Bourbigot, S.; Fontaine, G. Effects of Oxygen Concentration on the Reaction to Fire of Cross-Laminated Timber in a Controlled-Atmosphere Cone Calorimeter. *Fire Technol.* **2024**, 1–26. [CrossRef]
46. Mindeguia, J.C.; Mohaine, S.; Bisby, L.; Robert, F.; McNamee, R.; Bartlett, A. Thermo-Mechanical Behaviour of Cross-Laminated Timber Slabs under Standard and Natural Fires. *Fire Mater.* **2021**, *45*, 866–884. [CrossRef]
47. Wiesner, F.; Randmael, F.; Wan, W.; Bisby, L.; Hadden, R.M. Structural Response of Cross-Laminated Timber Compression Elements Exposed to Fire. *Fire Saf. J.* **2017**, *91*, 56–67. [CrossRef]
48. Bøe, A.S.; Hox, K.; Mikalsen, R.F.; Friquin, K.L. Large-Scale Fire Experiments in a Cross-Laminated Timber Compartment with an Adjacent Corridor—Partly and Fully Protected with a Water Sprinkler System. *Fire Saf. J.* **2024**, *148*, 104212. [CrossRef]
49. Bøe, A.S.; Friquin, K.L.; Brandon, D.; Steen-Hansen, A.; Ertesvåg, I.S. Fire Spread in a Large Compartment with Exposed Cross-Laminated Timber and Open Ventilation Conditions: #FRIC-02-Exposed Wall and Ceiling. *Fire Saf. J.* **2023**, *141*, 103986.
50. Cheng, C.-H.; Chow, C.-L.; Yue, T.-K.; Ng, Y.-W.; Chow, W.-K. Smoke Hazards of Tall Timber Buildings with New Products. *Encyclopedia* **2022**, *2*, 593–601. [CrossRef]
51. Frangi, A.; Just, A.; Hakkarainen, J.; Schmid, J.; Werther, N. Eurocode 5 Revision—Fire Design of Timber Structures. In Proceedings of the 10th International Network on Timber Engineering Research (INTER 2023), Biel/Bienne, Switzerland, 20–24 August 2023.
52. Hayajneh, S.M.; Naser, J. Fire Spread in Multi-Storey Timber Building, a CFD Study. *Fluids* **2023**, *8*, 140. [CrossRef]

53. Sun, Q.; Turkan, Y.; Fischer, E.C. A Building Information Modeling-Fire Dynamics Simulation Integrated Framework for the Simulation of Passive Fire Protection in a Mid-Scale Cross-Laminated Timber Compartment: Numerical Implementation and Benchmarking. *Fire Mater.* **2023**, *47*, 525–541. [CrossRef]
54. Li, X.; Yue, K.; Zhu, L.; Lv, C.; Wu, J.; Wu, P.; Li, Q.; Xu, C.; Sun, K. Relationships between Wood Properties and Fire Performance of Glulam Columns Made from Six Wood Species Commonly Used in China. *Case Stud. Therm. Eng.* **2024**, *54*, 104029. [CrossRef]
55. Xing, Z.; Wang, Y.; Zhang, J.; Ma, H. Comparative Study on Fire Resistance and Zero Strength Layer Thickness of CLT Floor under Natural Fire and Standard Fire. *Constr. Build. Mater.* **2021**, *302*, 124368. [CrossRef]