RESISTANCE OF TIMBER COLUMNS UNDER FIRE

Aala Halimi

A final thesis presented to

Escola Superior de Tecnologia e Gestão

Instituto Politécnico de Bragança

To the fulfilment of the master degree requirements in

Construction Engineering

Supervisor:

Prof. Dr. Paulo Alexandre Gonçalves Piloto (IPB)

July 2025

Acknowledgements

I would like to extend my heartfelt thanks to everyone who contributed to the realization of this report and supported me throughout my university journey.

Firstly, I am deeply grateful to my professional supervisor at the Instituto Politécnico de Bragança, Mr. Paulo Piloto, for his exceptional mentorship, technical insights, and unwavering support during my internship. His knowledge and direction have greatly enriched my experience and skills. I am also immensely appreciative of my academic supervisor, Mr. Issam Khezami, and all the faculty and staff at the Université Libre de Tunis, whose guidance, encouragement, and expertise have been instrumental in my progress and development in civil engineering. Their dedication to teaching and support has greatly enriched my academic experience and provided me with a strong foundation for my future.

Furthermore, I would like to thank the faculty and staff of both the Université Libre de Tunis and the Instituto Politécnico de Bragança for their dedication and for providing an environment that fosters learning and development. My gratitude extends to all my classmates and colleagues who have supported me and shared this journey.

Lastly, I express my deepest thanks to my family, whose love, encouragement, and sacrifices have been the foundation of my achievements. Your belief in me has been my greatest motivation. Thank you for always being by my side.

Abstract

This research investigated the fire resistance of timber columns through large-scale fire tests and advanced numerical simulations. The experiments were conducted according to the ISO 834 standard and measured charring rate, load-bearing capacity, fire resistance and failure mechanisms. The results showed that the timber columns maintained significant structural integrity over a considerable period and that the insulation material effectively improved fire resistance. Finite element models validated with experimental data provide accurate predictions of thermal and structural behaviour. The findings highlight the need for fire safety measures and advanced modelling techniques to ensure the safety of timber structures under fire scenarios. Future research will involve hybrid systems and innovative fire protection technologies.

Key words: Timber columns, fire resistance, charring rate, bearing capacity, finite element modelling, fire protection.

Resumo (PT)

Esta investigação investigou a resistência ao fogo de colunas de madeira através de ensaios de incêndio em larga escala e simulações numéricas avançadas. As experiências foram conduzidas de acordo com a norma ISO 834 e mediram a taxa de carbonização, a capacidade de carga, a resistência ao fogo e os mecanismos de falha. Os resultados mostraram que as colunas de madeira mantiveram uma integridade estrutural significativa durante um período considerável e que o material isolante melhorou eficazmente a resistência ao fogo. Os modelos de elementos finitos validados com dados experimentais fornecem previsões precisas do comportamento térmico e estrutural. Os resultados destacam a necessidade de medidas de segurança contra incêndio e técnicas de modelação avançadas para garantir a segurança das estruturas de madeira em cenários de incêndio. Pesquisas futuras envolverão sistemas híbridos e tecnologias inovadoras de proteção contra incêndios.

Palavras-chave: Colunas de madeira, resistência ao fogo, taxa de carbonização, capacidade de suporte, modelação por elementos finitos, Proteção ao fogo.

INDEX

INDEX OF FIGURES

INDEX OF TABLES

1- General introduction

Timber's sustainability, aesthetic appeal, and positive environmental impact have made it a material of choice for modern construction. The utilisation of wood in structural applications, such as multi-story buildings, is increasing as urbanisation becomes more intense and the need for environmentally friendly building materials increases. Nonetheless, the intrinsic flammability of wood poses serious questions about how well it will fare in a fire. Thorough research into the fire resistance of timber columns is necessary to ensure the safety of timber structures in the event of a fire. This study's main goals are to comprehend how fire-exposed timber columns behave and to create plans to increase their fire resistance. This calls for an all-encompassing strategy that combines numerical modelling and experimental testing. Empirical information on the thermal deterioration, charring rates, and structural integrity of wood columns exposed to fire is provided by experimental fire tests. These tests, which replicate actual fire situations and enable a consistent assessment of fire resistance, are carried out in accordance with accepted standards like ISO 834 and ASTM E119. Advanced finite element models are created concurrently to mimic the intricate relationships that exist between the thermal and structural behaviours of wood columns exposed to fire. To guarantee accuracy and dependability, these models are verified against experimental data. This provides insightful information about how timber structures behave in different fire scenarios. The goal of combining experimental and numerical methods is to pinpoint the important variables that affect fire resistance, such as the effects of moisture content, column sizes, and fire-retardant applications. The effectiveness of protective claddings and fire-retardant treatments in improving the fire performance of timber columns is also investigated in this study. In the event of a fire, these precautions are essential for extending the safe evacuation period and averting structural collapse. The results of this study should guide the safe design and construction of timber structures by informing building codes and standards. In conclusion, a greater understanding of wood columns' fire resistance is necessary for the use of wood in construction to become more widely accepted. To lay the groundwork for safer, more durable timber buildings in fire-prone areas, this study aims to close the knowledge gap.

2- State of the art

2.1- Fire Behaviour of Timber Columns

The fire performance of timber columns has been a critical research area for decades, especially concerning their charring rates, thermal degradation, and load-bearing capacity under fire conditions. Initial investigations began before 1980, laying a foundation for understanding how timber behaves when exposed to fire. König (1955) [14] was one of the first researchers to investigate the thermal breakdown of wood, showing how the creation of a charred layer acts as insulation to shield the inner uncharred portion from heat. This finding was crucial in showing that timber columns can retain their structural integrity in fire situations for long periods, even with surface damage. Likewise, Elliott (1954) [4] offered important observations on the fire resistance of wooden columns, adding to the initial recommendations on wood's behaviour during fires. His work emphasised how crucial timber is in retaining its load-bearing capacity when exposed to fire.

In a study conducted by Ingham (1952) [11], the fire performance of timber was compared to that of steel and concrete. It was determined that timber's ability to maintain strength longer during a fire made it a safer material, leading to changes in construction methods. Fons (1946) [5] extensively studied the combustion mechanisms of wood, pinpointing essential elements that impact the initiation and speed of burning. This initial research on wood burning supplied crucial information for comprehending how timber reacts during the beginning of a fire. Expanding this idea, Harmathy (1967) [10] presented the idea of char's ability to insulate, which restricts additional burning and hinders the transfer of heat to the unburned centre. This idea became pivotal in the development of fire-resistant design for timber buildings.

Lie (1967) [15] played a crucial role in advancing the knowledge of heavy timber's ability to resist fire, specifically concerning charring rates and the way different sizes of timber react to flames. His study showed that thicker wood sections burn at a slower rate, leading to increased fire resistance. After that, Saito (1975) [18] examined how heat is distributed in wood when exposed to fire, demonstrating the char layer's role as a protective barrier against high temperatures. Gerhards (1979) [8] studied how the strength of timber decreases as temperatures rise, focusing on its mechanical properties during fire exposure. This study was essential in determining the duration timber columns can maintain their ability to bear loads during fires. Schniewind (1970) [20] advanced knowledge on how timber reacts to elevated temperatures, recognising trends of thermal softening and structural weakening that were later incorporated into fire-resistance models.

In the 1960s, Buchanan and Cowper came up with the idea of the "effective residual section," which is the amount of timber area left after charring [1]. This idea enabled engineers to determine the remaining load-bearing capacity of timber columns in the event of a fire. Furuta and Furukawa (1970s) [7] showed how slow heat spread in big timber parts increases their fire durability, contributing crucial information for current fire safety rules. Additional significant findings were presented by Schaffer (1966) [19], demonstrating the ability of timber columns to sustain their structural toughness over long periods when subjected to fire, as well as by Fosberg and Marchant (1968) [6], emphasizing the innate fire resistance of timber attributed to its gradual charring characteristics.

In their 1975 study, Chowdhury and Hartley [2] investigated the behaviour of timber columns under fire-induced axial loads. They discovered that instead of sudden failure, timber gradually loses strength, offering a crucial safety buffer. Malhotra (1974) [17] also examined rates of charring and remaining strength, providing valuable knowledge for designing fire-resistant timber. In the 1970s, Janssens [12] studied how different types of wood charred at varying rates, aiding in the creation of fire safety standards tailored to each species. Beyer (1977) [21] examined glued laminated timber (glulam) and found that these engineered wood products have better fire resistance because they char slowly and have larger c
oss-sections. Additionally, research conducted by the Forest Products Research Laboratory during the 1950s-1970s [22] supplied extensive information on timber charring rates, playing a significant role in shaping current fire design codes.

2.2- Advancements in timber column fire resistance in recent times

Since 1980, research on timber fire performance has advanced by incorporating new materials and testing methods to improve understanding. In their book Structural Design for Fire Safety, Buchanan & Abu (2003) [1] offered contemporary tactics for creating timber structures that are resistant to fire. Their research highlights the ability of timber columns to meet contemporary fire safety standards when paired with insulation and fire-retardant treatments.

Lourenço & Pina (2013) [2] presented their research on examining timber columns in a fire. Their study yielded extensive information on the charring rates and effectiveness of various wooden components. Similarly, Görlacher (2016) [3] provided new design principles in his book Fire Safety Design for Timber Structures, which integrate the most recent research on timber's ability to resist fire.

Keller & Rapp (2020) [4] focused on recent progress in experimental research on the fire behaviour of wooden columns. Their analysis emphasised how critical the char layer is in reducing heat transfer rates and maintaining structural integrity. Clouston & Eastwick (2018) [5] offered a thorough review in the Fire Safety Journal on the historical and contemporary studies regarding the fire resistance of timber columns, highlighting the gradual weakening of timber when exposed to fire.

These new studies expand on the earlier research from before the 1980s, integrating contemporary understandings of engineered timber products like glulam, and offering creative strategies to improve the fire resistance of timber buildings. These advancements, when combined, guarantee the ongoing progress of fire-resistant timber building techniques and establish a strong foundation for upcoming research.

2.3- Experimental tests of timber columns under fire

With the growing use of wood in contemporary construction, researchers have focused their attention on the fire resistance of timber columns. To guarantee the safety and dependability of timber columns, experimental testing offers vital insights into how the materials behave in a fire. Typically, these tests evaluate important performance parameters like charring rate, load-bearing capacity, and failure modes by adhering to standard protocols like ISO 834 and ASTM E119.

Full-Scale Fire Testing: Full-scale fire tests are carried out in specially designed furnaces that mimic typical fire circumstances. Through observation of the material's charring and progressive loss of structural integrity, these tests quantify the thermal degradation of timber. Researchers use sophisticated instruments, such as displacement transducers, strain gauges, and thermocouples, to monitor temperature profiles, deformation, and structural failure.

Load-Bearing Capacity: Timber columns are mechanically loaded during fire exposure to replicate actual conditions. These tests demonstrate the columns' capacity to support loads and retain structural integrity in the face of thermal deterioration. The findings show that variables like cross-sectional dimensions, moisture content, and type of wood can significantly affect performance.

Fire Retardant Treatments: One important area of research is the application of fire-retardant treatments. Treated wood columns are more fire resistant overall because they frequently show delayed ignition and lower rates of charring. Quantitative data on the efficacy of different fire safety precautions can be obtained through comparative testing between treated and untreated columns.

Failure Modes: During testing, buckling, connection failures, and loss of load-bearing capacity because of charring are common failure modes seen. Developing strong construction practices and enhancing fire safety designs requires an understanding of these failure mechanisms.

2.4- Numerical simulation of timber columns under fire

Numerical simulations are an essential tool for understanding and forecasting the fire behaviour of timber columns, and they serve as a complement to experimental tests. These simulations model the intricate relationships between thermal and structural dynamics during fire exposure using cutting-edge computational techniques.

Finite Element Modelling (FEM): The most common technique for simulating timber column fire performance is finite element modelling (FEM). The mechanical behaviour at high temperatures, thermal conductivity, and material properties are all included in detailed FEM models. To guarantee accuracy, these models are verified and calibrated using experimental data.

Thermal-Structural Analysis: Coupled thermal-structural analysis sheds light on the relationship between heat transfer and timber's mechanical characteristics. This method simulates the process of charring, the resulting decrease in cross-sectional area, and the effect on load-bearing capacity. It finds crucial locations of structural weakness and predicts the time-to-failure.

Parametric Studies: Comprehensive parametric studies are made possible by numerical simulations, which assess the effects of various variables like column size, shape, load conditions, and fire-retardant treatments. By optimizing design parameters, these studies contribute to increased fire resistance.

Validation and Calibration: Thorough validation against experimental data is necessary to guarantee the dependability of numerical models. Models are refined through analysis of differences between simulated and observed data, thereby increasing their predictive power.

Hybrid Systems and Innovations: The simulation of hybrid timber systems, which combine wood with steel or concrete to enhance fire performance, is one recent development. Through simulations, novel strategies are also investigated, such as the integration of novel fire-retardant technologies and active fire protection systems.

Integration and future directions: A comprehensive understanding of the behaviour of timber columns under fire is provided by the integration of numerical and experimental approaches. Accurate design guidelines and fire safety standards require this kind of synergy. Subsequent investigations will try to improve simulation methods even more, investigate new fire safety strategies, and expand research to include hybrid systems and various kinds of wood. As experimental testing and numerical modelling continue to progress, timber structures will become more fire-safe and more widely used in sustainable construction methods. Researchers can help ensure that timber is used in the built environment in a safe, resilient, and environmentally friendly manner by filling in knowledge gaps and enhancing fire resistance techniques.

3- Timber standards and applications

3.1- Wood in civil engineering: standards and regulations

The increased use of wood in civil engineering, particularly for high-rise and structural applications, has driven the development of standards and regulations to ensure safety, durability, and sustainability. Standards vary across regions, but several international and national organisations provide guidelines to govern wood use in construction. These standards address aspects like load-bearing capacity, fire resistance, and environmental impact, ensuring that wood-based structures meet rigorous building codes.

3.1.1- Standards and Codes

- ISO 834: This standard pertains to fire resistance testing for different construction materials, such as wood. It offers guidelines for assessing material performance in fire situations and sets standards for charring rates, remaining strength, and structural stability.

- EN 1995-1-1 (Eurocode 5): A detailed European guideline for the structural engineering of timber constructions. It contains instructions for assessing load-bearing capacity, moisture resistance, and stability in different loading scenarios.
- EN 13501-2: Offers fire classification for building materials, encompassing wooden components. It specifies fire resistance durations (in minutes) and directs design to meet necessary fire safety in wooden structures.
- EN 14080: Regulates glued laminated timber (glulam), outlining criteria for structural integrity, material characteristics, and manufacturing standards.

3.1.2- Wood in building construction

Wood has been a vital building material for ages, esteemed for its durability, adaptability, and sustainability. In recent years, there has been a revival in the utilisation of wood in civil engineering and architecture, especially in major and tall structures. This revived interest is fuelled by an emphasis on sustainable building practices, progress in engineered wood materials, and breakthroughs in fire safety and structural modelling methods.

Here is a summary of wood's role in civil engineering, ranging from conventional applications to contemporary engineered timber buildings.

3.1.3- Advantages of wood

Wood offers several unique benefits for construction:

- Sustainability: Compared to steel and concrete, wood has a lower carbon footprint and is a renewable resource. Additionally, as they grow, trees store carbon, and sustainable forestry methods help to lower carbon emissions.
- Strength-to-Weight Ratio: Wood is a sensible option for long spans and lightweight structures because of its strength-to-weight ratio, which enables it to support substantial loads in relation to its weight.
- Thermal and Energy Efficiency: Wood's superior natural insulating qualities lower energy expenses and improve building efficiency.
- Acoustic and Aesthetic Features: Wood offers both aesthetic appeal and inherent warmth. It is frequently used for sound insulation in theatres, concert halls, and residential buildings due to its favourable acoustic qualities.

3.1.4- Types of engineered wood for structural applications

The development of engineered wood products has broadened the scope of wood applications in structural engineering, allowing it to be used for various load-bearing elements and architectural features:

- Cross-Laminated Timber (CLT): CLT is made of several layers of wood planks stacked and glued in perpendicular directions, creating a strong, stable material. Its rigidity and dimensional stability make it ideal for walls, floors, and roofs in both residential and commercial buildings.
- Glued Laminated Timber (Glulam): Composed of layers of lumber bonded with strong adhesives, glulam is suitable for beams, columns, and arches. Its high load-bearing capacity and durability allow for long spans in open spaces, such as in gymnasiums, auditoriums, and bridges.
- Laminated Veneer Lumber (LVL): LVL is made from thin layers of wood veneers glued together with the grain running in one direction. This creates a material with high tensile strength along its length, making it ideal for headers, beams, and rim boards in structural framing.

Each of these engineered wood types provides high strength and stability, while offering design flexibility for both aesthetic and functional purposes in buildings.

Figure 1: Piece of GLT.

3.1.5- Wood applications

Wood is extensively utilised in many civil engineering applications outside of buildings, such as:

- Bridges: Due to their great durability and aesthetic value, glulam and CLT are frequently used in pedestrian and vehicular bridges.
- Wooden walls and piles are frequently used in soil stabilisation and foundation projects.
- Acoustic Barriers and Sound Walls: Due to its capacity to absorb sound, wood can be used to create noise barriers alongside roads and railroads.

3.2- Fire Safety and structural integrity

3.2.1- Advancing fire safety

When building with wood, fire safety is the top priority, especially for tall structures. Fire resistance testing is guided by standards such as EN 13501-2 and ISO 834, which set requirements for both protected and unprotected timber. Finite element analysis (FEA) models, like those made in ANSYS, are frequently used in these standards to forecast how timber will behave under thermal stress. Limiting conditions, such as the 300°C charring rate model for residual cross-section calculation, and fire protection measures.

Fire safety is also covered by Eurocode 5 and the National Design Specification (NDS). Eurocode 5 permits the design of fire-resilient timber structures. Ensuring fire safety is a significant challenge when using wood for large buildings. When wood is exposed to fire, it chars, which can lower its ability to support loads.

However, advancements in fire protection and modelling help mitigate these risks:

- Fire-Resistant Design: Coatings like gypsum or fire-retardant materials serve as protective layers that delay the charring in engineered wood buildings, giving occupants additional time to exit and maintaining structural integrity.
- Thermal Analysis and Finite Element Modelling: In civil engineering, software like ANSYS is used to perform finite element analysis (FEA), simulating the effect of high temperatures on timber structures. This analysis predicts how wood will char and degrade under fire conditions, guiding design improvements.

3.2.2- Fire safety challenges in modern wooden high-rises

Wood is increasingly used as an eco-friendly material in tall buildings, but it poses significant fire risks. High-rise wooden structures are especially vulnerable due to wood's flammability and the potential for fires to spread between floors. Critical areas like joints and connections are at higher risk because heat can weaken adhesives and structural integrity. Buildings with high occupancy, such as apartments, hotels, and offices, face greater safety concerns. To address these risks, examples like the “Ascent” tower in Milwaukee and the “HoHo Tower” in Vienna use fire-resistant materials and specialized designs to enhance fire safety.

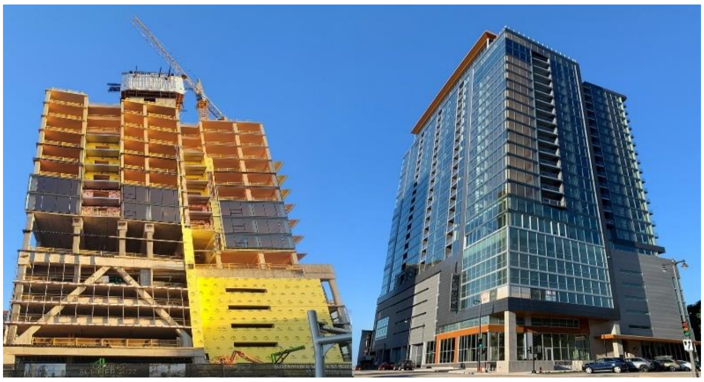


Figure 2: Ascent tower in USA.

3.2.3- Environmental impact and sustainability

When compared to more traditional building materials like steel and concrete, using wood is thought to be more environmentally friendly. Trees absorb CO_2 as they grow, and wooden buildings can store carbon for many years, reducing greenhouse gas emissions Wood is a popular choice for eco-friendly construction due to sustainable sourcing and the push for carbon-neutral buildings.

Man-made climate change – caused by more than a century of burning fossil fuels and releasing CO2 into the atmosphere – threatens our cities and our collective future. Wood, one of humanity’s oldest construction materials, offers a path to a more sustainable built environment. An emerging system of building materials called Mass Timber is being used in ways that avoid the “carbon cost” of traditional high-rise construction in concrete and steel. And wood is a renewable resource when forests are responsibly managed.

The technology of Mass Timber relies on manufacturing wood products that are much bigger, stronger, fire-resistant, and more durable than common lumber or plywood. Architects and builders use computers to design and precisely construct or cut giant puzzle pieces of structure that are transported to and assembled on site. To date, Mass Timber building systems have been used in only around 100 high-rises worldwide since the first 9-

story project in 2009. But its popularity is spreading, and buildings are growing taller, with structures up to 18 stories now covered by the International Building Code.

Mass Timber can greatly reduce the harmful environmental impact of new buildings.

The traditional materials of high-rise construction, steel and concrete, are produced by extractive industries that mine and heat the raw materials, thereby consuming even more carbon – called “embodied energy.” By contrast, during photosynthesis trees turn sunlight into oxygen and capture and store, or “sequester,” carbon long term. Compared to conventional concrete and steel construction, the use of Mass Timber can reduce Greenhouse Gas Emissions by up to 60 percent.

Tall buildings multiply these benefits, especially through high-density urbanism. This exhibition examines recent tall buildings in Mass Timber and proposals for its role in a more sustainable, low-carbon future for our cities and our planet.

4- Fire resistance of timber columns

4.1- Introduction

Ensuring fire safety in building design is crucial, particularly when combustible materials like timber are used. The EN 13501-2 standard in Europe, released in September 2009, offers a systematic method for assessing the fire resistance of construction products and building elements by utilizing data from fire resistance tests, excluding ventilation services. This guideline determines the duration a structural element can maintain its strength when subjected to fire, with ratings varying from R15 to R360. This document examines timber columns as crucial structural components and investigates their ability to withstand fire as outlined in EN 13501-2. We will explore the measurement of fire resistance, the factors affecting timber columns' fire exposure, and ways to improve their fire performance in building design.

4.2- Overview of EN 13501-2 fire classification

EN 13501-2 delineates fire resistance categorisations that determine the duration during which building materials and structural components can uphold their intended purpose during a fire. The categorisation depends on three main factors: load-bearing capacity (R), integrity (E), and insulation (I). The most important classification for timber columns is the

"R" rating, which evaluates their load-bearing ability in case of fire exposure. This standard guarantees that the building components can resist fire for a specific time, stopping any structural failure and enabling safe exit and firefighting activities. The fire resistance ratings for wooden columns are specified in minutes, indicating the duration of time they can sustain their load-bearing capacity. The standard outlines the fire resistance categories as: R 15, R 20, R 30, R 45, R 60, R 90, R 120, R 180, R 240, and R 360.

4.2.1- Fire resistance classes for timber columns

Timber, being an organic material, chars when exposed to fire. This charring process creates a protective layer that insulates the remaining timber from heat, thus preserving its structural integrity for some time. Based on EN 13501-2, timber columns are classified into different fire resistance classes, ranging from R 15 to R 360, depending on their ability to retain load-bearing capacity during fire exposure.

- **R 15 to R 60:** Timber columns treated with fire retardant coatings or constructed with engineered wood products such as glulam typically fall into this range. These columns can resist fire for up to 60 minutes, making them suitable for smaller structures or buildings with shorter evacuation times.

- **R 90 to R 120:** Timber columns designed for larger structures may achieve fire resistance of up to 120 minutes by increasing the cross-section size and using fire retardant treatments. These classifications are often required in public buildings, commercial spaces, or multi-story structures.

- **R 180 and Above:** In some cases, hybrid systems, which combine timber with other materials such as concrete or steel, can achieve fire resistance ratings of R 180 to R 360. These systems are typically used in high-rise buildings or critical infrastructure where higher fire resistance is essential.

4.2.2- Factors affecting timber columns' fire exposure

Several factors can increase the exposure of timber columns to fire, influencing their performance during a fire event. Understanding these factors is essential for ensuring the columns meet the necessary fire resistance classifications. Timber is naturally combustible and chars when exposed to fire, with the rate of charring affecting its ability to maintain structural capacity. Larger cross-sections slow charring and help protect the column's core, extending its load-bearing function during a fire. Untreated timber, however, is more vulnerable, as the absence of flame-retardant treatments or intumescent coatings allows faster combustion, which can lead to premature failure. In buildings with a high fire load—large amounts of flammable materials—the rapid spread of fire increases heat exposure to timber, reducing its fire endurance. Additionally, poor ventilation can trap heat and smoke, further exposing timber columns, while proper ventilation and fire compartmentalization can help control fire spread and reduce structural exposure. Finally, load-bearing timber columns supporting critical areas need sufficient fire resistance to prevent collapse, as inadequate load distribution can lead to instability during fire exposure.

Enhancing the Fire Resistance of Timber Columns: Different methods can be used to improve the fire resistance of timber columns to meet EN13501-2 standards.

Increase Cross-Section Size: Bigger timber columns have higher fire resistance because they char at a slower pace. Expanding the cross-sectional area enables a prolonged period of Carrying capacity while exposed to fire.

Apply flame retardant treatments: Applying fire retardant treatments prolongs the charring process, enabling the wood to maintain its structural strength for extended periods. These treatments are essential for enhancing the fire resilience of wooden columns in residential and Commercial structures.

Use intumescent coatings: Intumescent coatings increase in size when they come into contact with elevated temperatures, creating a protective barrier that shields the wood from direct heat. This greatly increases the duration that timber columns can resist fire.

Hybrid systems: which involve combining timber with non-combustible materials like steel or concrete, can improve fire resistance. One way to enhance the fire resistance of timber columns is by surrounding them with concrete or adding steel reinforcement, without compromising their ability to support weight.

Compartmentalization and fire barriers: Proper compartmentalization in building design can help isolate fires and protect timber columns from prolonged exposure. Fire barriers such as fire-rated walls and ceilings further enhance the fire performance of timber structures.

4.3- Importance of testing and certification

The fire resistance ratings specified in EN 13501-2 are determined using information from standardised fire resistance assessments. These assessments determine the duration a structural component can uphold its ability to bear weight, remain intact, and provide insulation in a controlled fire environment. Timber columns need to be tested in order to assess their fire resistance and obtain certification. Certification ensures that timber columns meet necessary fire resistance levels and are suitable for particular building uses. Testing labs, in accordance with EN 13501-2 procedures, provide certifications after obtaining results, confirming the product meets fire safety regulations.

Finally, Timber columns, key elements in sustainable construction, must meet fire resistance standards set by EN 13501-2. Designers and engineers can enhance fire performance by increasing cross-sections, using fire retardants, or adopting hybrid systems. As timber gains popularity for its aesthetic and environmental benefits, compliance with fire safety standards remains crucial for protecting lives and property.

Here is a summary table for fire resistance classifications according to EN 13501-2, focusing on timber columns and their respective fire ratings:

Table 1: Fire resistance and evacuation times for different types of construction

Type of Construction	Fire Protection Level	Fire Resistance Rating (Minutes)	Estimated Safe Evacuation Time (Minutes)	Description
Unprotected Timber Construction	No fire protection	R15 – R30	5 – 10	Basic timber construction with no flame-retardant treatments or fire protection.
Protected Timber Construction	Fire-retardant coatings or treatments	R45 – R 60	10 – 20	Timber treated with flame retardants, coatings, or intumescent paints.
Hybrid Timber (Wood + Concrete/Steel)	Timber encased in fire-resistant materials	R90 – R120	20 – 30	Timber columns integrated with concrete or steel for enhanced fire resistance.
Non-Combustible Construction	Non-combustible materials (steel, concrete)	R120 – R240	30 – 60	Construction made of materials like reinforced concrete, steel, or masonry.
High-Rise and Critical Buildings	Full fire-resistant systems	R180 – R360	60+	Tall buildings, public spaces, or critical infrastructure with advanced fire protection systems.

Unprotected timber buildings, with minimal fire resistance (R 15 to R 30), require quick evacuation—typically within 5 to 10 minutes—due to rapid fire spread. In contrast, protected timber construction, treated with flame retardants, achieves fire resistance of R45 to R60, allowing 10 to 20 minutes for evacuation.

Hybrid timber buildings, incorporating materials like concrete or steel, offer enhanced resistance (R90 to R120), providing a safe evacuation window of 20 to 30 minutes. Non-combustible constructions, made from materials like reinforced concrete, achieve ratings of R120 to R240, allowing 30 to 60 minutes for evacuation. High-rise and critical buildings, equipped with advanced fire protection, offer the highest fire resistance (R180 to R360) and evacuation times exceeding 60 minutes, maximising safety in severe fire scenarios.

Figure 3: Fire Damage in Exposed Timber Construction (AI generated).

When exposed timber construction is exposed to high temperatures, the wood chars and loses its strength, resulting in fire damage. If the fire is not contained, it may result in total collapse and structural instability as the timber's capacity to bear weights declines.

5- Materials

5.1- Glued laminated timber

5.1.1- Generality

Wood is a remarkable and versatile material that plays a vital role in our lives in numerous ways. Beyond being a source of comfort, protection, and a natural raw material, young trees in forests perform a crucial function by absorbing harmful CO2, storing carbon, and releasing oxygen into the atmosphere.

Wood's uses are diverse and impressive, ranging from simple items like wooden spoons to musical instruments, art objects, furniture, and even advanced products for solid wood structures. We encounter this unique material daily, and its qualities—such as strength, durability, stability, and fire resistance—highlight its intelligence. Moreover, wood positively impacts human well-being and health.

Glulam (GL24) is prized for its versatility in both structural and architectural applications, combining strength with aesthetic appeal. In addition to large open spaces and decorative applications, glulam’s engineered composition makes it ideal for complex structures like trusses, cantilevers, and floor beams. Its strength grade, GL24, is often chosen for load-bearing roles in both residential and commercial buildings, due to its high resistance to bending and compressive forces. Thanks to its layered construction with moisture-resistant adhesives, glulam also performs well in environments with fluctuating humidity levels, such as those defined by Categories 1 to 3 in EN 1995-1-1. These categories specify moisture conditions that range from heated indoor spaces to fully exposed outdoor environments, ensuring glulam’s adaptability across varied climates.

5.1.2- Glulam GLT categories according to EN 1995-1-1

Category 1: This category is characterised by a moisture content in the materials that corresponds to a temperature of 20° C and a relative humidity of the ambient air exceeding the value of 65% only for a few weeks annually (heated inside space).

Category 2: This category is characterised by a moisture content in the materials that corresponds to a temperature of 20° C and a relative humidity of the ambient air exceeding the value of 85% only for a few weeks annually (protected outside space).

Category 3: This category is characterized by climate conditions that result in higher levels of moisture content than in category 2.

5.2- glulam GL24

Glued laminated timber (glulam) is a highly engineered wood product made by gluing together layers of timber. GL24, a common strength grade of glulam, is frequently used in structural applications due to its high strength, dimensional stability, and aesthetic appeal. Understanding the fire resistance of GL24 glulam columns is essential for ensuring the safety and durability of timber structures in fire-prone environments.

To form a glulam component, wood laminations (dimensional lumber) are arranged in accordance with their performance characteristics that are rated for stress in order to form a glulam component. The longest lifespan and proportionate stress absorption are typically ensured by sandwiching the beam with the strongest laminations. Long spans are possible because the laminations are joined end to end and bonded together with a strong, moisture-resistant adhesive. To increase the member's strength, the laminations' grains run parallel to their length.

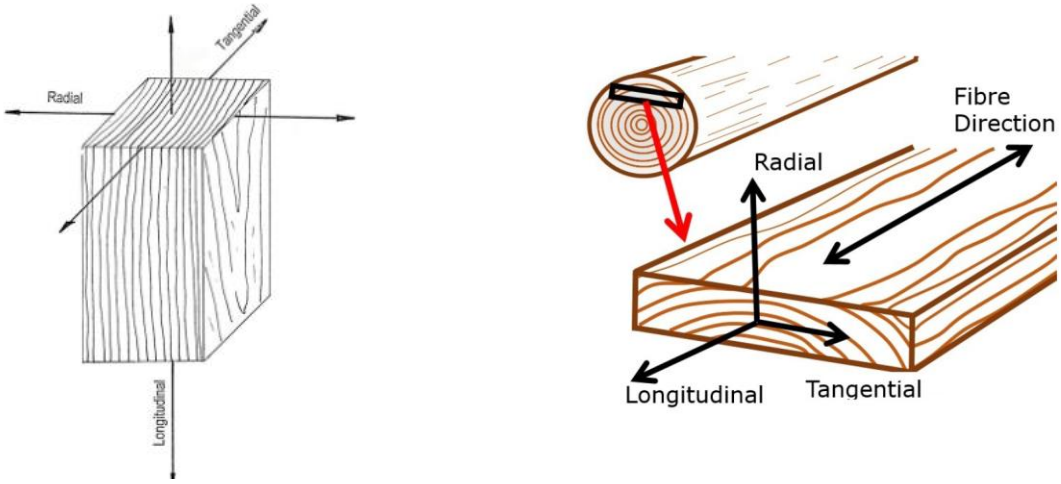


Figure 4: Cross section with orientation.

Table 2: Wood Fibre Orientations in Glued Laminated Timber

Wood Fiber Orientation	Description	Strength Characteristics	Application
Longitudinal	Parallel to the grain, following the wood’s length	High tensile and compressive strength	Used for structural members, beams, and columns
Radial	Perpendicular to the growth rings, from centre to bark	Moderate strength; resists splitting along growth rings	Useful in curved glulam members
tangential	Tangent to growth rings, around the tree’s circumference	Less stable, susceptible to warping and shrinkage	Mostly avoided in high-stress areas,

Glued laminated timber, is a versatile material that is renowned for both its strength and aesthetic appeal. By using strong adhesives to join layers of wood, the lamination technique allows wood to be used for longer spans without losing strength. This makes it ideal for designing large spaces where both aesthetics and functionality are important, like churches, gymnasiums, and auditoriums. The material is popular for exposed beams and vaulted ceilings because of its ability to support heavy loads while maintaining a fashionable, organic appearance.

In addition to its architectural uses, glulam finds application in a variety of structural components, such as beams, columns, and frames. It can also be engineered into more complex structures, such as cantilevers, purlins, and trusses, providing flexibility in design. This makes it suitable for commercial buildings, educational institutions, and residential projects alike. For instance, many higher education facilities employ glulam to create impressive, open interiors that are both functional and visually appealing.

The strength-to-weight ratio of glulam is another important characteristic, allowing its use in challenging applications such as floors, decking, and roofs. It can be moulded into tailored profiles to meet needs, whether for an exclusive architectural style or a distinct structural necessity. The sustainability of the material is a factor in its increasing popularity, as it is derived from renewable resources and can be obtained from responsibly managed forests.

Additionally, glulam's fire and weather resistance, when properly treated, improves its longevity in various environmental situations. Ultimately, glulam comes in various appearance grades, enabling designers to select the appropriate choice based on the project's visual objectives. Architectural-grade glulam provides a sleek, premium finish for visible uses, whereas industrial and framing grades are better for concealed structural purposes. This versatility in both function and appearance makes glulam a favoured option for projects where sustainability, strength, and design are crucial.

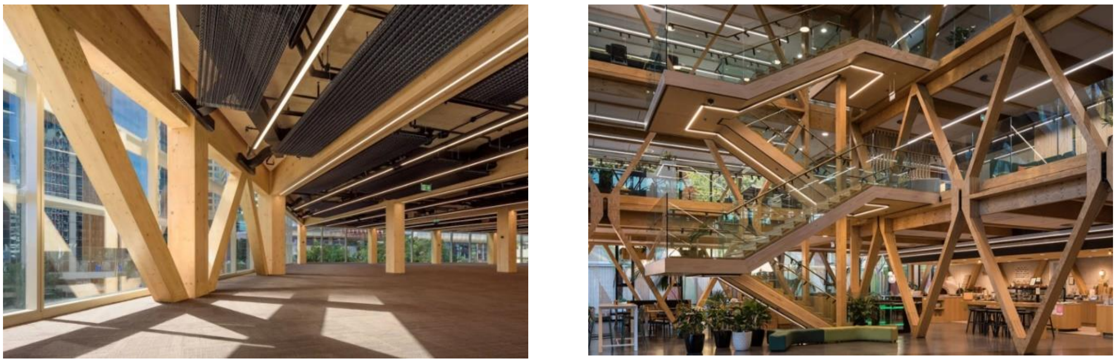


Figure 5: Application of GLT in Modern Construction.

5.2.1- Mechanical behaviour (EN 1995-1-1)

GL24 glued laminated columns, whether they are homogeneous or combined, demonstrate specific mechanical characteristics as outlined in EN 1995-1-1 (Eurocode 5). Columns made of Homogeneous GL24 comprise layers of wood with even strength properties across them, ensuring reliable load-bearing capacity and strong resistance to compression and bending. When GL24 columns are combined, they have stronger outer layers and weaker inner layers to focus strength where it is most necessary, enhancing material efficiency.

Both varieties demonstrate strong stiffness, with a high modulus of elasticity, and excel in axial compression and compression-bending load situations, making them ideal for structural applications requiring stability and strength.

Table 3: Mechanical behaviour of the GL24.

		Combined glulam GL24c	**Homogeneous GL24h**
N/mm^2	Defluxion ($f_{m,g,k}$)	24	24
	Tension: parallel ($f_{t,0,g,k}$)	17	19.2
	Tension: at right angles ($f_{t,90,g,k}$)	0.5	0.5
N/mm^2	Module of elasticity: parallel ($E_{0,g,mean}$)	11.00	11.500
	Module of elasticity: at right angles($E_{90,g,mean}$)	300	300
	Shear modulus ($G_{g,mean}$)	650	650
Kg/m^3	density$_{g,k}$	365	385

5.2.2- Timber columns in combined compression and bending

Timber columns are commonly utilised in different structures because of their durability, eco-friendliness, and attractive appearance. The stability of these columns is mainly determined by their slenderness ratios when they experience axial compression or both compression and bending. The EN1995-1-1 standard offers a comprehensive guide for determining these proportions, with specific attention given to the variations in bending around the y-axis and z-axis.

This study investigates the slenderness ratios, $\lambda_{\mathrm{reel,y}}$ *and* $\lambda_{\mathrm{reel,z}}$, through theoretical models and analytical methods.

The relative slenderness is crucial for assessing the buckling stability of timber columns under different loading conditions. They are defined as:

$$\lambda_{\mathrm{rel,y}} = \frac{\lambda_{\mathrm{y}}}{\pi}\sqrt{\frac{f_{\mathrm{c,0,k}}}{E_{0,05}}} \tag{1}$$

$$\lambda_{\mathrm{rel,y}} = \frac{\lambda_{\mathrm{y}}}{\pi}\sqrt{\frac{f_{\mathrm{c,0,k}}}{E_{0,05}}} \tag{2}$$

Where: λ_{y} and λ_{z} are the geometric slenderness ratios corresponding to bending about the y-axis and z-axis, respectively.

$f_{\mathrm{c,0,k}}$ Is the characteristic compressive strength of the timber parallel to the grain.

$E_{0,05}$ is the 5th percentile modulus of elasticity parallel to the grain.

These formulas express the relative slenderness in terms of material properties and column dimensions, helping to predict buckling behaviour under axial compression and bending.

Where both $\lambda_{\mathrm{reel,z}} \leq 0{,}3$ and $\lambda_{\mathrm{reel,y}} \leq 0{,}3$ the stress should satisfy the expressions:

$$\left[\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right]^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m\frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{3}$$

$$\left[\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right]^2 + k_m\frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{4}$$

Our goal is to determine the value of the compressive strength without fire:

$$N_{b,rd} = \left[\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right]^2 \leq 1 \tag{5}$$

If we have $\lambda_{\text{reel,y}} \geq 0{,}3$ the stress should satisfy the expressions:

$$N_{b,rd,f_i} = \frac{\sigma_{c,0,d}}{k_{c,y} \times f_{c,0,d}} \leq 1 \tag{6}$$

$$k_{c,y} = \frac{1}{K_y + \sqrt{K_y^2 - \lambda_{reel,y}^2}} \tag{7}$$

$$K_y = 0{,}5 + \left[\, 1 + \beta_c\left(\lambda_{\text{reel,y}} + 0{,}3\right) + \lambda_{reel,y}^2\right] \tag{8}$$

β_c is a factor for members within the straightness limits, which takes 0.2 for solid timber and 0.1 for glued laminated timber and LVL.

This study examines the stability of timber columns, focusing on their slenderness ratios in relation to axial compression and bending moments, which impact buckling behaviour. Relative slenderness ratios $\lambda_{\text{reel,y}}$ and $\lambda_{\text{reel,z}}$, based on EN 1995-1-1 standards, helps assess stability by considering the y-axis and z-axis orientations, respectively.

Timber, as an orthotropic material, exhibits different mechanical properties along its grain (longitudinal) and across its grain (transverse), influencing its strength and deformation characteristics in various directions. This orthotropic nature of timber makes it essential to evaluate bending stability in both primary axes, enabling more precise predictions of the column's response under load.

5.2.3- Thermal behaviour (EN 1995-1-2)

The emissivity coefficient should be considered as 0.8 for uncharred and charred timber surfaces, as well as fire protection materials. Specified values for thermal conductivity, specific heat capacity, and density, depending on temperature, are considered effective for standard fire exposure in EN 1995-1-2.

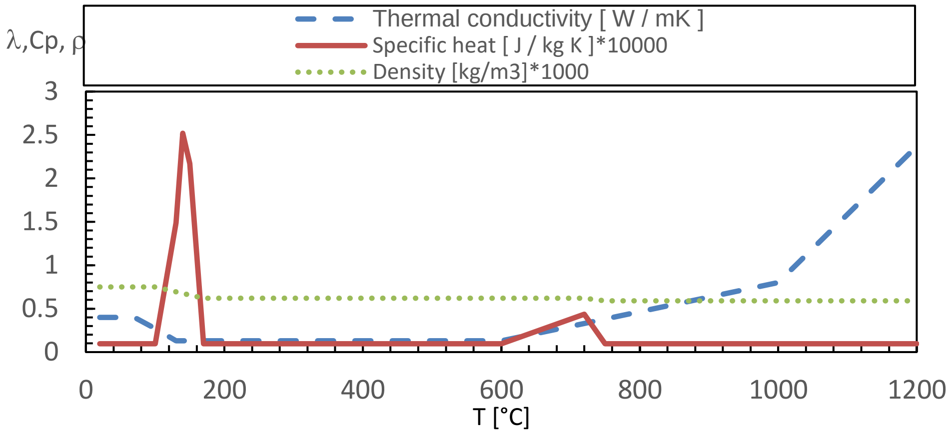


Figure 6: Thermal properties of glulam

The graph shows the thermal properties of glulam, specifically thermal conductivity, specific heat capacity, and density, in relation to temperature.

- Thermal Conductivity (dashed blue line): As temperature increases, the thermal conductivity of glulam remains relatively low until around 600°C, after which it increases sharply. This suggests that at higher temperatures, heat transfer through glulam becomes more efficient, which can affect its fire resistance.
- Specific Heat Capacity (solid red line): The specific heat shows an initial peak, likely due to moisture evaporation around 100°C, then stabilizes at lower values. This stabilization reflects reduced energy absorption in high-temperature zones, typical as the material transitions to char.
- Density (dotted green line): Density decreases gradually with temperature, indicating progressive charring and material degradation, which aligns with EN 1995-1-2’s guidelines on glulam’s charring rate.

This thermal behaviour emphasizes glulam's charring protective layer, which limits inner heat transfer, thereby enhancing fire resistance.

5.2.4- Thermal actions for temperature analysis

In temperature evaluation for fire-affected buildings, thermal effects are denoted by the net heat flux h_{net} applied on the exterior of the component. This calculation of net heat flux considers both convective and radiative heat transfer processes, representing the heat taken in by the material from nearby flames and heated gases. Convective heat transfer relies on the temperature variation between the surface and the adjacent gas, whereas radiative heat transfer is affected by the material's emissivity and the level of thermal radiation. Collectively, these elements offer an all-encompassing assessment of heat input, essential for precisely forecasting temperature increases and material responses in fire situations.

$$\mathrm{h}_{\mathrm{net}} = \mathrm{h}_{\mathrm{net,c}} + \mathrm{h}_{\mathrm{net,r}}[W/m2] \tag{9}$$

$$\mathrm{h}_{\mathrm{net,c}} = \alpha_{\mathrm{c}} \,.\, (\Theta_{\mathrm{g}} - \Theta_{\mathrm{m}})[\mathrm{W/m2}] \tag{10}$$

$$\mathrm{h}_{\mathrm{net,r}} = \emptyset \,.\, \varepsilon_{\mathrm{m}} \,.\, \varepsilon_{\mathrm{f}} \,.\, \sigma \,.\, [\,(\Theta_{\mathrm{r}} + 273\,)^4 - (\Theta_{\mathrm{m}} + 273\,)^4][\mathrm{W/m2}] \tag{11}$$

Table 4: Parameters for convective and radiative heat transfer

Notation	Description	Value/Units
$\boldsymbol{\alpha_c}$	Coefficient of heat transfer by convection	$[\mathrm{W/(m^2K)}]$
$\boldsymbol{\Theta_g}$	Gas temperature in the fire compartment	[°C]
$\boldsymbol{\Theta_m}$	The surface temperature of the member	[°C]
$\emptyset$	The configuration factor	1,0
$\boldsymbol{\varepsilon_m}$	The surface emissivity of the member	0,8
$\boldsymbol{\varepsilon_f}$	the emissivity of the fire	1,0
$\boldsymbol{\sigma}$	The Stefan Boltzmann constant	$5{,}67.10^{-8}$ $[\mathrm{W/m^2K^4}]$
$\boldsymbol{\Theta_r}$	The effective radiation	[°C]

Table 5: Nominal fire curves

	Θ_{g}	α_c
Standard fire curve	$20 + 345\, log_{10}(8t + 1)$	$25\, W/m^2k$
External fire curves	$660(1 - 0.687e^{-0.32t} - 0.313^{-3.8t}) + 20$	$25\, W/m^2k$
Hydrocarbon fire curves	$1080(1 - 0.325e^{-0.167t} - 0.675^{-2,5t}) + 20$	$50\, W/m^2k$

5.3- Gypsum plasterboard

Gypsum, known as calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$), is extensively utilized in construction due to its fire-resistant and thermal insulation characteristics, particularly as gypsum plasterboard. This material is crucial in civil engineering, particularly for internal divisions and ceiling coverings. The standards ISO 834, EN 1995-1-2, EN 1363, and EN 13501 dictate the performance criteria for gypsum regarding fire resistance and thermal behaviour, guaranteeing that gypsum-based products satisfy essential safety standards for structural uses.

5.3.1- Gypsum in civil engineering

Gypsum plasterboard is commonly used in civil engineering for interior walls, partitions, and ceilings because of its fire resistance and thermal insulation features. Every one of these standards offers directives to guarantee uniform performance and safety of gypsum materials in construction applications:

- ISO 834 specifies fire-resistance testing methods, describing the processes for subjecting construction components to heat and assessing their fire resistance.
- EN 1995-1-2 addresses fire design in timber structures, detailing requirements for materials such as gypsum that ensure fire resistance.
- EN 1363-1 outlines general testing protocols for fire resistance that are relevant to building materials, assisting in determining a benchmark for gypsum's behavior in fire situations.
- EN 13501-2 is the European standard that governs the fire classification of building materials, grouping them according to their fire response and duration of resistance, which is essential for assessing gypsum plasterboard's performance in fire situations.

5.3.2- Mechanical behaviour

Gypsum plasterboard functions effectively under compression and moderate flexing, yet it is still quite brittle and has restricted tensile strength. The gypsum core provides strength and thermal insulation, whereas the paper facings improve its bending strength and add to its overall stability. At elevated temperatures, the board experiences an endothermic dehydration reaction, emitting water vapour that hinders heat transfer, thereby serving as a thermal barrier. This dehydration stage, along with its low thermal conductivity, renders gypsum plasterboard an essential material for fire safety, enhancing the fire resistance of walls, ceilings, and structural components in construction assemblies. Furthermore, the board's multi-layered structure aids in preventing distortion, preserving its strength in fire situations for an extended duration.

5.3.3- Fire resistance and thermal behaviour of gypsum plasterboard

The thermal characteristics of gypsum are crucial to its fire protection capabilities. When subjected to elevated temperatures, gypsum experiences an endothermic reaction that emits bound water in the form of steam. This procedure takes in heat, which reduces the rate of temperature increase in the structural materials that the gypsum safeguards. The standards outline techniques for assessing gypsum's behaviour in fire scenarios, especially regarding thermal insulation and duration of resistance. Figure 7 depicts the effective thermal properties of gypsum plasterboard.

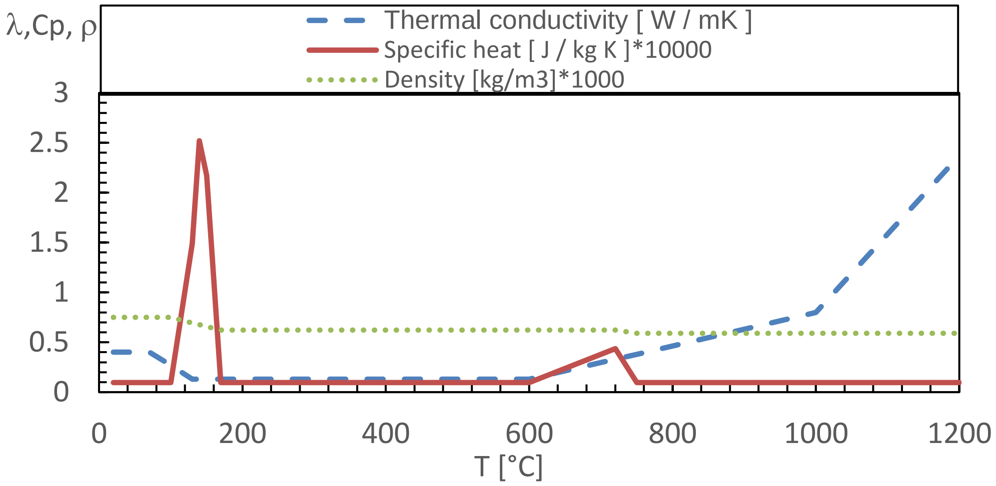


Figure 7: Thermal properties of the gypsum.

The subsequent characteristics of gypsum's thermal and fire-resistant attributes are key to its effectiveness:

- Thermal Conductivity: Gypsum exhibits low thermal conductivity, which progressively rises as it loses moisture upon heating, enabling it to function as an insulating layer that reduces heat transfer. EN 1995-1-2 focuses on this characteristic, as it aids in extending fire resistance by slowing down heat transfer to the materials beneath.
- Specific Heat Capacity: Due to its elevated specific heat capacity, gypsum takes in considerable heat, helping to regulate the temperature increase in nearby structural elements. This feature, detailed in EN 1995-1-2, is essential for preserving structural stability, as it prolongs the duration for adjacent materials to attain critical temperatures.

- Density: In the event of a fire, gypsum experiences a slight reduction in density due to water being released; nevertheless, it maintains its structural integrity, allowing it to provide thermal insulation and resistance to fire.
- ISO 834 and EN 1363 assess this characteristic by subjecting gypsum to regulated heating, mimicking fire scenarios to evaluate how long it can safeguard structural components.

The fire resistance duration of gypsum plasterboard can vary, with ratings typically ranging from 30 to 120 minutes or more. ISO 834 and EN 1363 further specify testing procedures, where gypsum boards are subjected to elevated temperatures to evaluate how effectively they maintain their properties during exposure to fire.

6- Design assisted by testing

6.1- Introduction

6.1.1- Classification of columns

Columns shall be tested in accordance with the EN 1365-4. The EN 1365-4 is a European standard that outlines the procedures for testing the fire resistance of columns. This standard is part of the EN 1365 series, which deals with fire resistance tests for various load-bearing elements. The standard applies to columns made from different materials, such as steel, concrete, timber, or composites and specifically examines evaluating the fire resistance of vertical load-bearing members known as structural columns.

The design of the specimen and the number of tests to be conducted should be based on a comparison between the intended field of application for the classification and the field of application for test results as defined in the standard. The test method provides crucial information on the test specimen or construction and the field of direct application of test results. Factors influencing the number of tests to be carried out include the range of exposure conditions to be covered, the range of end conditions (such as pin-jointed or fully rotationally restrained ends), the type and level of loading, and specific constructional details.

6.1.2- Test objectives and conditions

The primary objective of the test is to determine how long a column can maintain its structural integrity under fire conditions by measuring its ability to resist failure in terms of load-bearing capacity, thermal insulation, and, in some cases, integrity. To achieve this, the column is exposed to a controlled fire scenario within a furnace, following a specific temperature-time curve (often the standard ISO 834 fire curve), while being subjected to a pre-determined axial load that simulates the actual load it would carry in service.

6.1.3- Performance criteria

To make sure the column can support the weight without collapsing during the test, the load-bearing capacity of the column is evaluated. To determine how effectively it can regulate temperature increases on the non-exposed side based on the material and usage, it also looks at the thermal insulation properties. In addition, the test may evaluate the column's integrity to confirm that hot gases and flames are successfully prevented from passing through. To closely simulate real-world conditions, the columns are evaluated vertically, and comprehensive records regarding the column's height, dimensions, and material properties are maintained.

The column's ability to withstand fire exposure without losing its load-bearing function is measured in minutes, known as fire resistance. The data obtained from the EN 1365-4 test is essential in establishing the fire resistance rating of the column, which is critical for evaluations of building design and safety.

[Failure of load bearing capacity: (vertical element)

Axial contraction: $C= h/100$ (mm)

Rate of axial contraction: $dc/dt = 3h/1000$ (mm/min)]

6.2- Experimental test

In experimental testing, these columns are subjected to controlled fire exposure in a robust, rectangular furnace lined with refractory bricks to withstand high temperatures. The furnace has a large, insulated door for containment, side-mounted four gas burners for uniform heating, and sensors to measure temperature and performance under fire conditions. An overhead hoist allows safe handling of test specimens, ensuring that timber structures can be designed to protect lives and property effectively.

- In addition to providing uniform heating from all four sides, the furnace is equipped with advanced temperature sensors that capture real-time data, ensuring accurate monitoring of the column’s thermal response.
- The controlled environment allows researchers to observe how glulam columns behave structurally under both heat and mechanical stress, simulating real-life fire scenarios.
- The mechanism for applying a load is adjustable, allowing for variations in load intensity to better mimic different structural conditions that timber columns might face during a fire.
- Both the top and bottom anchoring steel cylinders help maintain the integrity of the setup, ensuring that the column remains stable throughout the test.

This setup not only provides a detailed assessment of fire resistance but also helps refine fire safety standards and improve construction practices for timber-based structures.

Figure 8: front view of the furnace

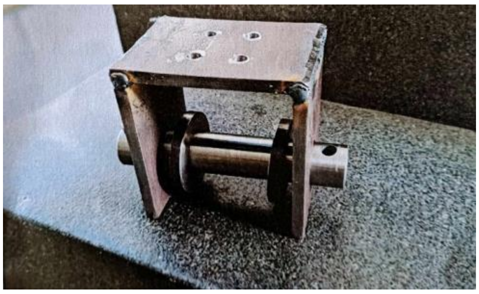


Figure 9: Steel support

6.3- Operating mode

Two elements were developed to carry out the test, the column, which is the main element and the dummy, which plays the role of a sample to measure the temperatures in different positions and to give us the modifications inside the column.

Table 6: section of the column and dummy

	COLUMN	DUMMY
Materials	GLT24h	GLT24h
$B \times H$ (mm)	100×80	100×80
Length (mm)	1300	400
Density (KG/m^3)	365	365

While testing timber columns for fire resistance, certain protocols are followed to guarantee precise temperature readings, even though the thermocouples used do not meet European standard EN 1363-1. Thermocouples used during the test are precise temperature sensors placed at strategic points on the timber column and inside the furnace. These devices measure the temperature in real-time, providing critical data on heat distribution, the rate of temperature rise, and the thermal response of the column under fire conditions. Before we fix the thermocouples, Connections are created at both ends of the column to guarantee stability and correct alignment. These drilled points enable the column to be firmly attached to the steel cylinders, accurately mirroring actual loading and support conditions in the fire test.

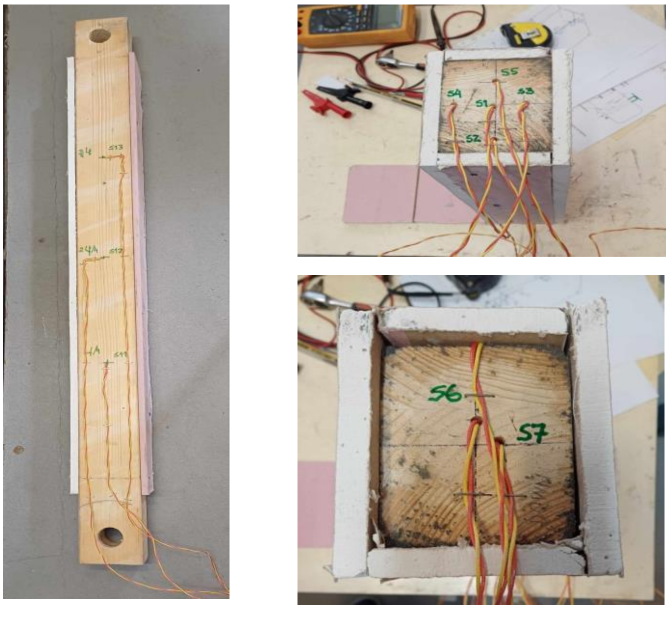


Figure 10: fixing of thermocouples.

In our case we have three thermocouples are strategically placed on the timber column to monitor its temperature response during fire exposure. These thermocouples provide data on temperature distribution and heat penetration within the column. These thermocouples should be placed at 1/4, 1/2, and 3/4 of the column's exposed length to ensure comprehensive thermal monitoring across its height (L_f) (see Appendix 1).

Additionally, the dummy is equipped with eight thermocouples to capture detailed thermal behaviour. Five thermocouples are positioned at the top of the dummy, drilled into its structure for accurate placement. Two thermocouples are located at the bottom, also installed via drilled holes. The final thermocouple, number eight, is placed in the middle of the dummy to provide temperature readings at its centre. This comprehensive thermocouple arrangement ensures thorough monitoring of temperature gradients and heat transfer throughout the dummy and the timber column, simulating realistic conditions and helping assess the fire performance accurately. (see Appendix 2)

During the test setup, a gypsum board layer measuring 12.5 mm thick is applied to shield part of the timber column, covering 1,060 mm of the 1,300 mm exposed section. This gypsum layer serves as a barrier against fire, slowing down the heat and charring of the timber below. The area shielded by gypsum is used to imitate some fireproofing measures, evaluating the performance of the column with and without protection when exposed to fire. The 240 mm section that is not covered at the top or bottom is open to direct fire, allowing for a comparison of thermal and structural performance in both the protected and unprotected regions.

In the AutoCAD drawing, cross-section “section A-A” likely shows the detailed placement of fasteners, such as screws, securing the gypsum board to the timber column. In “section A-A” the screws are positioned at regular intervals along the gypsum layer, ensuring that they are firmly attached to the timber column.

6.4- Test and results

6.4.1- Software results

Once the setup is complete, the timber column and dummy are securely placed inside the furnace, strategically aligned to ensure they are both exposed to the controlled fire conditions. Embedded thermocouples within the column and dummy play a crucial role in monitoring temperature changes throughout the test. These thermocouples are connected to data acquisition systems using insulated wires, which protect the signal integrity and prevent interference. The wires lead from the thermocouples to an external data logger or a specialized temperature measurement module, which acts as the interface between the sensors and the computer. This connection is vital for collecting accurate temperature readings during the experiment.

Figure 11: Preparation of the specimen inside the furnace.

The ISO 834 fire curve is a standard temperature-time profile that is utilised to replicate the heat dynamics of a fire inside a furnace when conducting fire resistance tests. This curve shows a slow rise in temperature, usually reaching around 1000°C (1832°F) in a span of 60 minutes. During a controlled fire simulation, the furnace is adjusted to mimic this pattern, establishing a situation where the temperature increases in a foreseeable way. The graph starts with a gradual rise, showing the initial stages of fire conditions, before quickly escalating to peak temperatures that may test the strength of columns. This consistent method enables reliable assessment of fire resistance in different materials and designs, guaranteeing that tested structures can endure practical fire situations

To ensure standard fire exposure, the furnace's average temperature is controlled to follow the time-temperature relationship.

$$T = 345\, log_{10}(8t + 1) + 20 \tag{12}$$

where ‘T’ is the temperature in degrees Celsius, and ‘t’ is the time in minutes. This formula represents the heating curve commonly used in fire-resistance tests, allowing for a consistent increase in temperature that simulates real fire conditions. By maintaining this curve, researchers can evaluate the material's performance under predictable, repeatable fire exposure conditions, ensuring accurate assessments of fire resistance for construction materials.

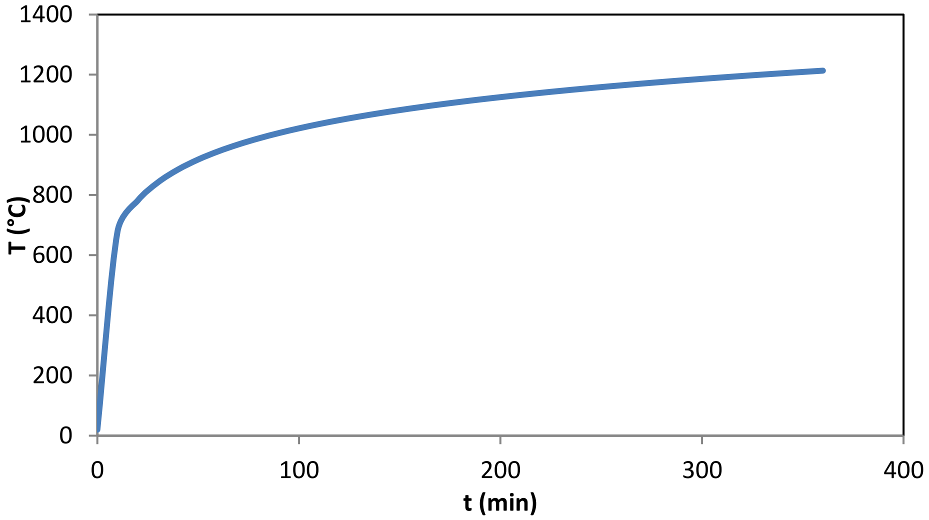


Figure 12: Standard time/temperature curve (ISO 834)

The load is considered constant throughout the test with a value of 36609N.

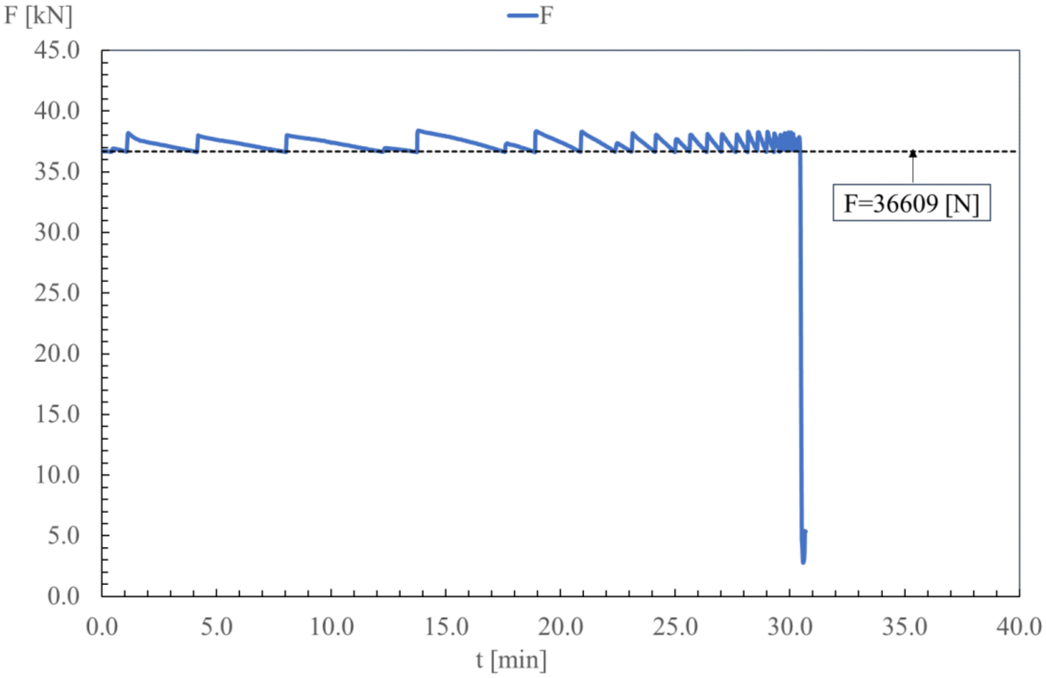


Figure 13: Load versus time curve

While conducting fire resistance testing on timber columns, axial contraction proves to be a crucial occurrence when the column is subjected to elevated temperatures. As the heat rises following the ISO 834 fire curve, the wood experiences thermal expansion at first, then goes through a notable deterioration of its structural characteristics, resulting in weakened strength. This procedure leads to the wood shrinking and contracting in the axial direction, which can be calculated and expressed as the axial contraction rate. The speed at which the wood shrinks may change depending on the kind of wood, how wet it is, and how hot and long it is exposed to heat. It is crucial to monitor the axial contraction of columns in fire tests to evaluate their behaviour, as too much contraction could result in buckling or a decrease in load-bearing capacity, ultimately affecting the stability of the structure. Having knowledge of these factors allows engineers to anticipate the behaviour of timber columns in actual fire situations and guides the creation of safer and more durable timber buildings. Axial contraction (C) occurs when the column's length decreases due to heat exposure, caused by the degradation and charring of the wood. This change shows how the material characteristics of the column change When exposed to fire, affecting its capacity to support weight. dC/dt is a way to quantify how fast the column shrinks as it is subjected to higher temperatures. This rate indicates when the wood changes from expanding to contracting due to temperature, highlighting crucial stages of structural weakness.

A faster axial contraction rate indicates quick weakening, potentially resulting in premature column failure. This measurement is crucial in assessing the fire safety and performance of wooden structures, leading the way in creating fireproof designs and safety precautions. Comprehending both C and dC improves predictive modelling and strengthens safety measures in building design to guarantee stability in the event of fire exposure.

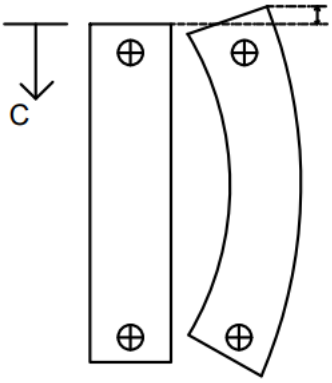


Figure 14: Behaviour of the column

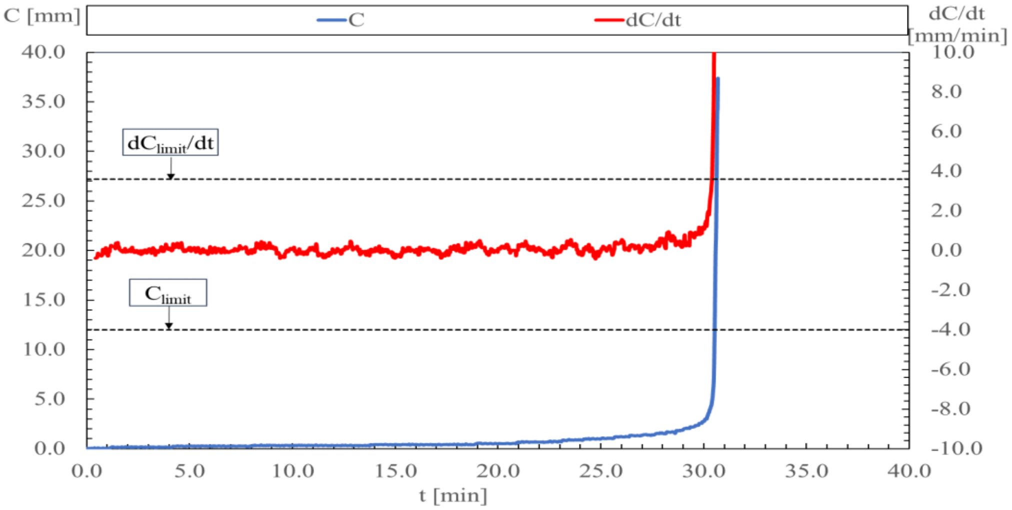


Figure 15: Axial and rate axial contraction curve.

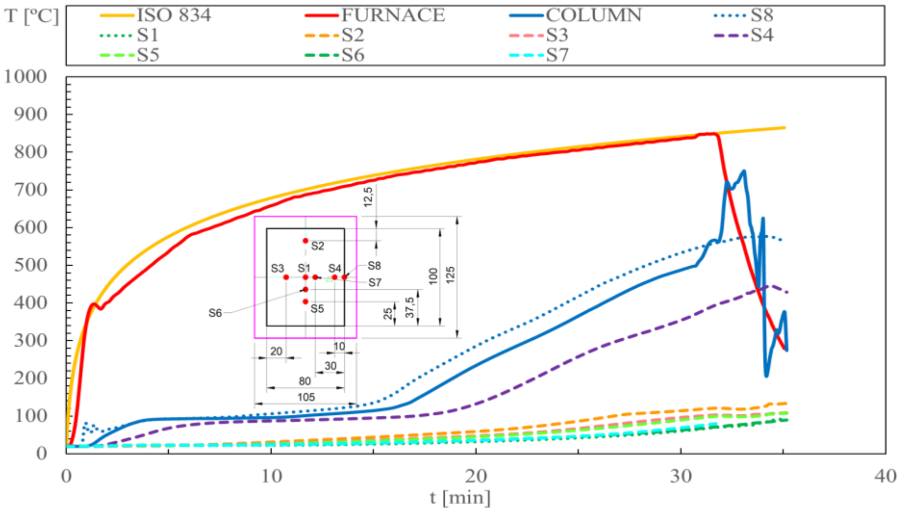


Figure 16: Dummy temperature results.

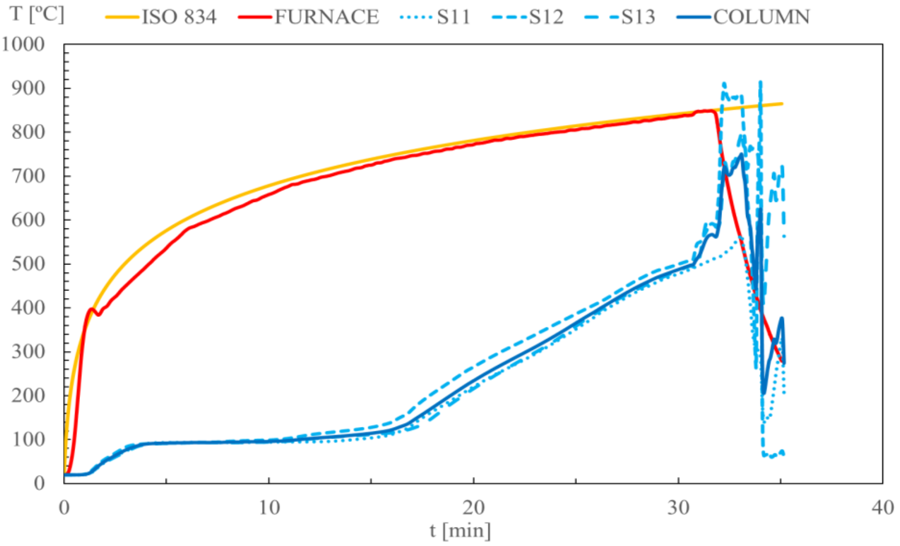


Figure 17: Column temperature results.

The yellow line represents the ISO 834 standard fire curve, which shows a steady and controlled increase in temperature up to about 900°C at 30 minutes. The red line, representing the actual furnace temperature, closely follows the ISO 834 curve, indicating that the furnace environment successfully replicated the standard fire conditions until around 30 minutes, where it peaks and then fluctuates. The temperature of the column (solid blue line) shows a gradual increase but at a significantly slower rate compared to the furnace. This reflects the insulating properties of the timber and the time it takes for heat to penetrate the material.

A sharp increase in temperature is observed around the 30-minute mark, indicating possible structural failure or rapid heat transfer through the column due to loss of integrity.

The dotted and dashed lines (S11, S12, S13) represent temperature readings at specific points or sensors on the column. These lines increase at different rates, suggesting non-uniform heating or varying thermal response within different sections of the column.

The furnace (red line) again mirrors the ISO 834 standard curve closely, showing consistent fire exposure until the 30-minute mark, followed by a sharp drop and subsequent fluctuations.

The temperature of the dummy specimen (solid blue line) shows a similar pattern to the column, with a steady increase and a sudden jump around 30 minutes, indicating a significant change in the thermal response, potentially a failure point or sudden heat transmission.

The dotted and dashed lines (S1 to S8) represent temperature readings at different points on the dummy. These show that some areas of the dummy experienced a faster temperature rise than others, implying uneven heating and different exposure levels or material responses.

6.4.2- Specimen results after test

Figure18 show the timber column after the fire test, with significant charring and structural deformation, especially near the loading point. Here’s an interpretation based on the observed details:

- Charring Depth (d_char): The initial image displays a detailed view of a timber column's cross-section, highlighting a clear charred layer encasing the inner, untouched wood. This charring depth of about **10 mm** ($\boldsymbol{d_0 = 7mm}$) corresponds with the predicted value from the theoretical charring model **(tfi,req = 28.64 minutes),** suggesting that the duration and conditions of fire exposure resulted in consistent outcomes. This implies that the fire resistance measures implemented functioned as expected, with the charred layer forming according to predicted thermal degradation.

- Ultimate Limit State and Structural Failure: The second image shows the tested column after failure, with severe damage near the loading zone. Fire exposure weakened the timber, especially in unprotected areas, leading to structural failure as it reached its ultimate limit state.

Figure 18: Specimen at the end of the test

Fire Protection Efficiency: The char marks and the depth imply that the safety measures (gypsum board on the protected part) succeeded in delaying fire penetration, while the unprotected areas experienced greater charring and structural harm. The distinction between protected and unprotected zones highlights the significance of fireproofing strategies in maintaining structural integrity.

In conclusion, the experimental arrangement offers an efficient approach for assessing the fire resistance of wooden columns by adhering to thorough protocols. Proper thermocouple positioning, pressure assessments, and consistent axial deformation monitoring are crucial for obtaining valid and significant information. The examination verifies that timber elements exposed directly to flames will experience considerable charring and weakening without proper fire protection. The measured charring depth and final failure close to the load point correspond with theoretical expectations, highlighting the significance of efficient fireproofing solutions. This method provides important understanding of timber columns' behaviour during fire scenarios, aiding the creation of safer, more robust wooden structures in structural use.

7- Simple calculation method

7.1- Scope of EN 1995-1-2

This document deals with the design of timber structures for the accidental situation of fire exposure and it is intended to be used in conjunction with prEN 1995-1-1 and prEN 1991-1-2.

This document applies to timber structures required to fulfil a load-bearing function, a separating function or both.

This document gives principles and application rules for the design of structures for specified requirements in respect of the functions and the levels of performance.

This document applies to structures, or parts of structures, that are within the scope of prEN 1995-1-1 and are designed accordingly.

The methods given in this document are applicable to all products covered by harmonised technical specifications referred to in this document.

Figure 19: EN 1995-1-2

This flowchart illustrates a calculation method for assessing the fire resistance of linear timber elements, distinguishing between protected and unprotected sections. For protected elements, it determines the start and duration of charring, adjusts the charring rate if protection fails, and calculates charring depth over time. For unprotected elements, it directly determines charring depth and then uses either reduced cross-sectional or material properties to calculate the element's load-bearing capacity.

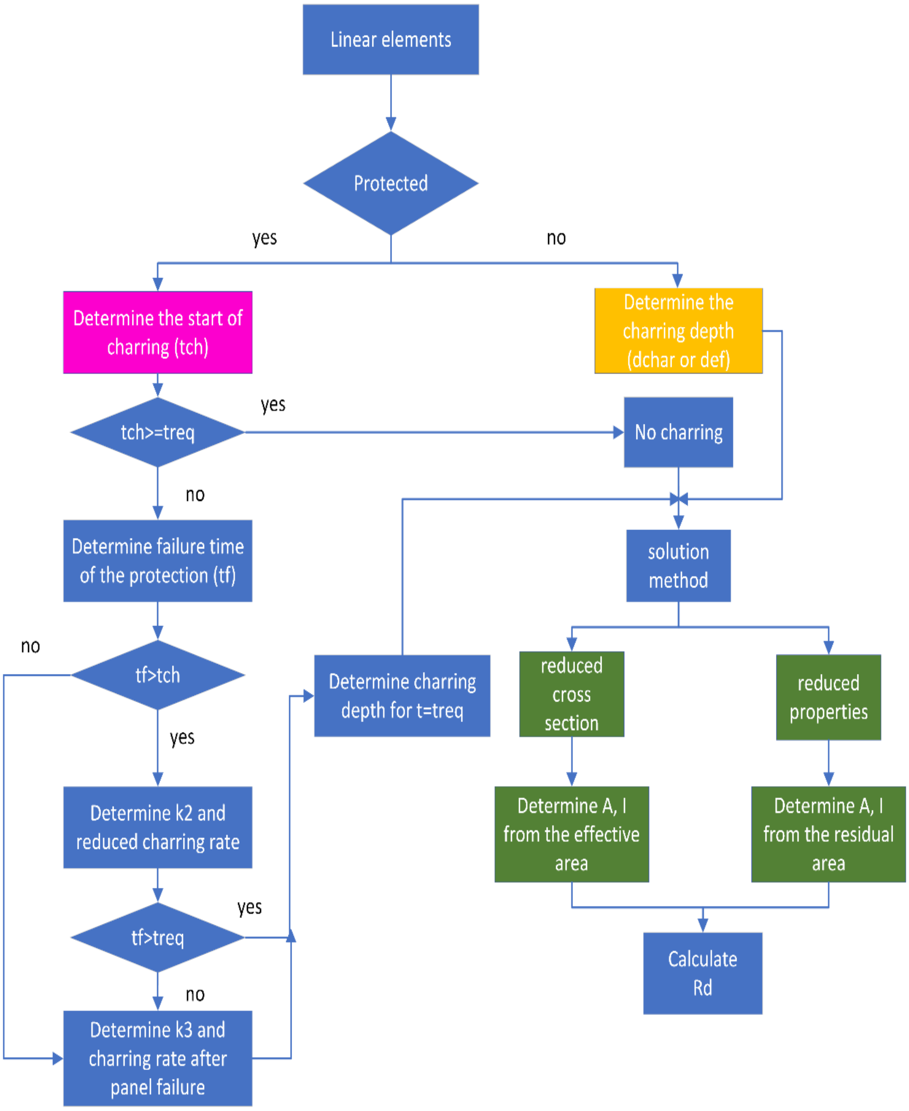


Figure 20: Flowchart for Fire Resistance Calculation of Protected and Unprotected Timber Elements

7.2- Design of unprotected timber elements

7.2.1- Example room temperature (RT)

To determine the load-bearing capacity of a simply supported timber column at room temperature, with a span of 1.2 meters between supports and a cross-sectional dimension of 0.100 m by 0.080 m, we use the material properties for GL24 timber. The calculation of

load-bearing capacity at room temperature will consider factors such as the material's compressive strength, column slenderness, and any applicable safety factors.
According to EN14080, the material properties are:

- $f_{m,g,k} = 24\ \mathrm{M}P\mathrm{a}$
- $f_{c,0,g,k} = 24\ \mathrm{M}P\mathrm{a}$
- $E_{0,g,mean} = 11.5\ \mathrm{G}P\mathrm{a}$
- $E_{0,g,05} = 9.6\ \mathrm{G}P\mathrm{a}$

Table 7: Load bearing capacity RT , using Eurocode without protection

GEOMETRY /PARAMETER/LOAD	**VALUE**	**UNITS**
h	0.100	m
b	0.080	m
L (Length)	1.20	m
L_e (buckling Length)	1.20	m
I_{zz}	$6.66667.10^{-6}$	m^4
i_z=$\sqrt{I_{zz}/A}$	0.03	m^4
λ=i/L_e (slenderness)	41.57	[-]
$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	0.66	[-]
$N_{cr} = \frac{\pi^2 E I_{zz}}{L_e^2}$	502619	N
$k_z = 0.5\left(1 + \beta_c\left(\lambda_{rel,z} - 0.3\right) + \lambda_{rel,z}^2\right)$	0.74	[-]
$k_{c,z} = \frac{1}{k_z + \sqrt{k_z^2 - \lambda_{rel,z}^2}}$	0.94	[-]
$\boldsymbol{N_{c,Rd} = N_{b,Rd} = k_{c,z} \times, f_{c,0,d} \times A}$	**180 871**	**[N]**

7.2.2- Example unprotected column under fire

An unprotected timber column exposed to fire will undergo charring, which reduces its cross-sectional area and diminishes its load-bearing capacity. The charring rate and the duration of exposure directly affect how much of the timber is lost, weakening the structure over time. This example illustrates the calculation process for determining the reduced capacity of an unprotected timber column under fire conditions by accounting for factors like charring depth, residual cross-section, and stability adjustments. The effective cross sections of timber are used to determine its load-bearing capacity, assuming that the mechanical properties are not affected by fire. Although the char layer is thin in the early stages of fire, the mechanical properties of the remaining wood still decrease due to thermal degradation of strength and stiffness.. The thickness of the char layer d_{ef} plays an Important role in its effectiveness is determined by:

$$d_{ef} = d_{char} + k_0 \times d_0 \tag{13}$$

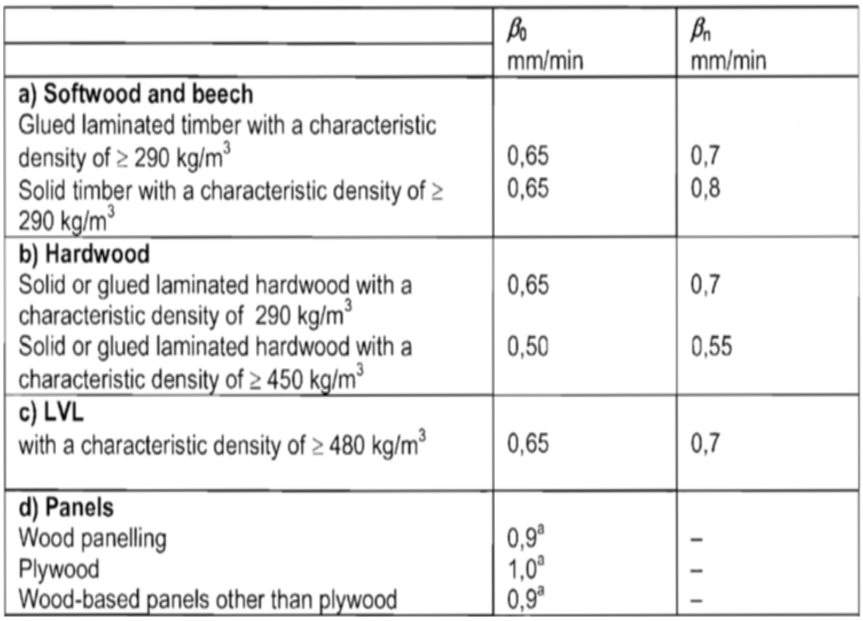
$$d_{ef} = \beta_n \times t_{fi} + k_0 \times d_0 \tag{14}$$

where d_{char} is the char layer thickness, d_0 = 7mm and k_0 is a coefficient dependent on fire resistance time t_{fi} .

Table 8: Charring rate factor k_0 [EN 1995-1-2]

t_{fi} [min]	k_0 [-]
$t_{fi} < 20$	$k_0 = t_{fi}/20$
$t_{fi} \geq 20$	$k_0 = 1.0$

Table 9: β_0 values



	β_0 mm/min	β_n mm/min
a) Softwood and beech		
Glued laminated timber with a characteristic density of ≥ 290 kg/m^3	0,65	0,7
Solid timber with a characteristic density of ≥ 290 kg/m^3	0,65	0,8
b) Hardwood		
Solid or glued laminated hardwood with a characteristic density of 290 kg/m^3	0,65	0,7
Solid or glued laminated hardwood with a characteristic density of ≥ 450 kg/m^3	0,50	0,55
c) LVL		
with a characteristic density of ≥ 480 kg/m^3	0,65	0,7
d) Panels		
Wood panelling	0,9[a]	–
Plywood	1,0[a]	–
Wood-based panels other than plywood	0,9[a]	–

- Glued laminated timber: $\beta_0 = 0{,}65$ / $\beta_n = 0{,}7$ (mm/min)

- New residual dimensions may be calculated, based on the number of exposed sides:

$$A_{residual} = (D - 2d_f) \times (B - 2d_f) \tag{15}$$

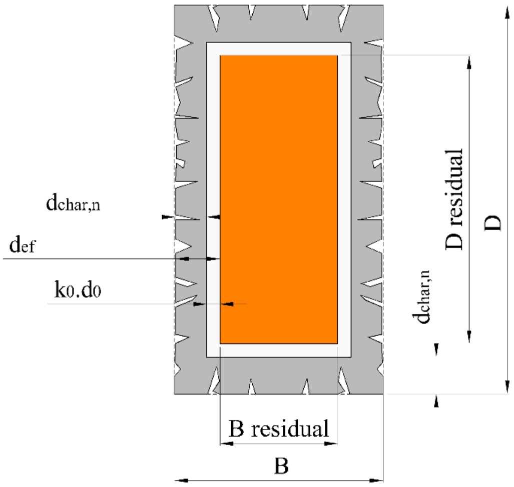


Figure 21: Cross section unprotected column

- Assuming the failure mode by compressive buckling around the strong axis.
- timber column, with 1.2 m between supports.
- fire resistance, t_{fi}=28.64 min. [EN 1995-1-2]
- The Material is GL24h with a density of 365 kg/m^3

Table 10: Column geometry

GEOMETRY /PARAMETER/LOAD	**VALUE**	**UNITS**
b * h	0.100*0.080	m
L_e (buckling Length)	1.20	m
I_{zz}	$6.66667.10^{-6}$	m^4
i_z=$\sqrt{I_{zz}/A}$	0.03	m^4
λ=i/L_e (slenderness)	41.57	[-]
$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	0.66	[-]

Table 11: Load bearing capacity unprotected under fire

GEOMETRY /PARAMETER/LOAD	**VALUE**	**UNITS**
d0	7	mm
ko	1	[-]
β_n	0.7	mm/min
$d_{char,n} = \beta_n \times t_{freq}$	20.04	mm
d_{ef}	27.04	mm
D residual	0.0459	m
B residual	0.0259	m
I_{zz}	$2.08803.10^{-7}$	m^4
i_z=$\sqrt{I_{zz}/A}$	0.013	m^4
λ=i/L_e (slenderness)	90.56	[-]
$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	1.44	[-]
β_c	0.1	[-]
$k_z = 0.5\big(1 + \beta_c(\lambda_{rel,z} - 0.3) + \lambda_{rel,z}^2\big)$	1.60	[-]
$k_{c,z} = 1/k_z + \sqrt{k_z^2 - \lambda_{rel,z}^2}$	0.44	[-]
$\boldsymbol{N_{c,\mathrm{fi},Rd} = N_{b,\mathrm{fi},Rd} = k_{c,z} \times, f_{c,0,d} \times A}$	**12 514**	**[N]**

Unprotected, under fire, the load bearing is $\mathbf{12\ 514}\ [\mathbf{N}] < \mathbf{180\ 871}[\mathbf{N}]$ When comparing the load-bearing capacity of a timber column under fire to its performance at room temperature, the capacity decreases significantly due to the reduction in cross-sectional area from charring.

7.2.3- Design of protected timber element

The process of charring in fire-protected timber structures follows a staged pattern depending on the time intervals and protection failure. Initially, charring starts at t_{ch}, governed by a normal rate βn. After a period, at t_f the protection layer fails, increasing the charring rate to βi due to direct exposure to fire. At a subsequent time t_a , the rate reverts to normal, though the depth might be capped at 25 mm. This staged progression allows us to estimate the charring depth, which is critical in assessing the structural integrity of timber exposed to fire over time.

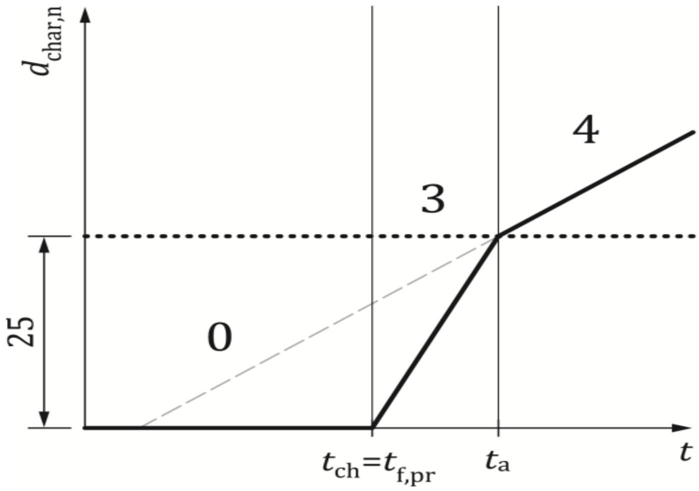


Figure 22: $\mathrm{d_{char}}$ over time [EN 1995-1-2]

- Assuming the failure mode by compression buckling around the strong axis.
- Calculate the Time of Start of Charring (t_{ch})

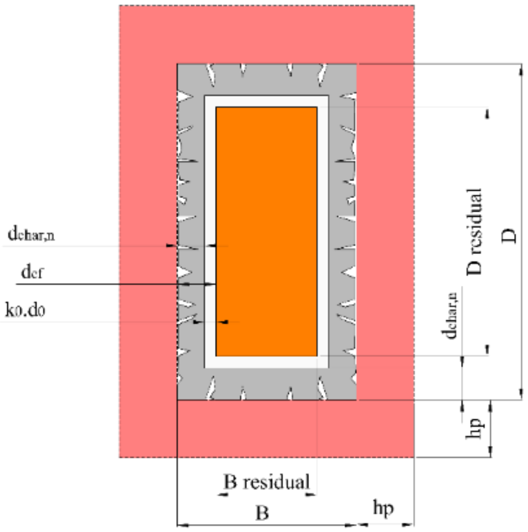


Figure 23: Cross section protected timber column

The formula for the time of start of charring when fire protection is present is:

$$t_{ch} = 2.8 \times h_p - 14 \qquad (16)$$

h_p is the thickness of the protection, in mm.

- The start of charring is delayed until time t_{ch}.
- Failure time of the protection layer (t_f)

Although some surface damage might start before the fire protection layer is fully compromised, this early charring is typically disregarded in simplified calculations. Once the protective material fails and no longer insulates the timber, the wood becomes directly exposed to high temperatures. As a result, the charring rate temporarily increases beyond its usual value. This period is particularly important, as the section of the timber begins to degrade more quickly, leading to a faster reduction in its load-bearing capacity. Recognizing and accounting for this accelerated deterioration phase is essential for ensuring structural safety in fire conditions.

$$t_a = min\begin{cases} 2\ t_f \\ \dfrac{25}{k_3\ \beta_n} + t_f \end{cases} \tag{17}$$

The notional charring depth ($d_{char,n}$) equals the charring depth of the same unprotected cross-section; or
Charring depth equals 25 mm ($k_3 = 2$).

Eurocode 5 states that fire protection delays timber charring. After the protective layer fails, charring accelerates briefly before stabilizing. For protected wood, a standard char depth of 25 mm is often used.

Table 12: Load bearing capacity protected under fire

GEOMETRY /PARAMETER/LOAD	**VALUE**	**UNITS**
h_p	12.5	mm
t_{ch}	21	min
t_f	21	min
d0	7	Mm
ko	1	[-]
β_n	0.7	mm/min
t_a	38.86	Min
β_1	1.4	mm/min
$d_{char,n} = \beta_n \times t_{freq}$	10.70	Mm
d_{ef}	17.70	Mm
D residual	0.0646	M
B residual	0.0446	M
I_{zz}	$1.00251.10^{-6}$	m^4
i_z=$\sqrt{I_{zz}/A}$	0.019	m^4
λ=i/L_e (slenderness)	64.34	[-]
$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	1.02	[-]
β_c	0.1	[-]
$k_z = 0.5\big(1 + \beta_c(\lambda_{rel,z} - 0.3) + \lambda_{rel,z}^2\big)$	1.06	[-]
$k_{c,z} = 1/k_z + \sqrt{k_z^2 - \lambda_{rel,z}^2}$	0.53	[-]
$N_{c,\mathrm{fi},Rd} = N_{b,\mathrm{fi},Rd} = k_{c,z} \times, f_{c,0,d} \times A$	**51762**	[N]

Protected columns retain more strength than unprotected ones:

- Protected under fire: **51762 N**
- Unprotected under fire: **12514**

8- Advanced calculation method

In Chapter Advanced Calculation Method for evaluating the performance of timber columns in fire scenarios, we can utilize advanced tools such as the Finite Element Method (FEM), particularly through software like ANSYS, to simulate both protected and unprotected timber columns. Here's an outline of the essential principles, techniques, and their relevance to modelling timber columns under fire conditions.

8.1- Overview of ANSYS Software

ANSYS is a robust computational tool utilized for structural, thermal, and fluid analyses, along with various other simulation types. It enables engineers to replicate real-world scenarios, such as fire exposure, on intricate structures. In this instance, ANSYS can assist in modelling the behaviour of wooden columns when subjected to higher temperatures by:

- Modelling material degradation over time due to fire exposure
- Simulating thermal and structural interactions for both protected and unprotected timber columns
- Performing finite element analysis (FEA) to understand how materials, like timber, perform structurally under fire conditions.

8.2- Finite Element Method (FEM) Basics

FEM is a numerical technique that divides complex structures into small elements, making it possible to analyse stresses, strains, and deformations under various conditions. Each of these elements is connected by **nodes**, which are points where calculations are conducted to determine how each part of the structure behaves under load.

In This case:

- Timber columns are divided into small finite elements.
- Each node represents a small portion of the column's geometry.
- As fire affects the column, these nodes calculate stress, strain, temperature, and load-bearing capacity.

8.3- Advanced Calculation of Timber Columns under Fire Conditions

In this advanced analysis, ANSYS software and the Finite Element Method (FEM**)** are used to simulate the behaviour of a timber column under fire, protected with gypsum with a thickness of 12,5mm. The timber column, with a rectangular cross-section of 100mm×80mm and a length of 1.3m, is supported at intervals of 1.2m by cylindrical steel supports with a diameter of 40 mm (modelled in ANSYS with the element type SOLID185).

8.4- Overview of Material Properties and Orthotropic Characteristics

Timber is an orthotropic material, meaning it has distinct properties along its three primary axes:

- Elastic Modulus (E): In the timber column, the values for E_x, E_y, E_z, and E_y reflect the stiffness in the longitudinal and transverse directions, respectively, with the mean modulus of elasticity $E_{0,g,mean} = E_L$= $E_X =$ $11{,}5GPA$ / $E_{0,g,mean}$ = 9,6GPa.
- Bending and Compression Resistance: Set to 24MPA for the wood type GLT24h.
- Shear Modulus (G): This will be applied along with stiffness in the respective orthogonal directions.

The column material properties are temperature-dependent, with the analysis requiring temperatures at 20°C, 100°C, and 300°C. At higher temperatures, the wood's structural properties degrade due to charring, which we'll model in ANSYS by adjusting material properties at these temperature points.

The information in the following is obtained from: EN 1995-1-2, Wood Handbook as an Engineering Material 2010, and EN14080.

Table 13: Orthotropic parameters depending on the temperature

temperature	**20 °C**	**100 °C**	**300 °C**
$\boldsymbol{E_L = E_X}$	1.15E+10	4.025E+09	1.15E+08
$\boldsymbol{E_R = E_Y}$	8.97E+08	3.1395E+08	8.97E+06
$\boldsymbol{E_T = E_Z}$	4.945E+08	1.7308E+08	4.945E+06
$\boldsymbol{V_{LR} = V_{XY}}$	0,372	0,372	0,372
$\boldsymbol{V_{RT} = V_{YZ}}$	0,435	0,435	0,435
$\boldsymbol{V_{LT} = V_{XZ}}$	0,467	0,467	0,467
$\boldsymbol{G_{LR} = G_{XY}}$	7.36E+08	2.576E+08	7.36E+06
$\boldsymbol{G_{RT} = G_{YZ}}$	3.45E+07	1.2075E+07	3.45E+05
$\boldsymbol{G_{LT} = G_{XZ}}$	7.015E+08	2.4553E+08	7.015E+06

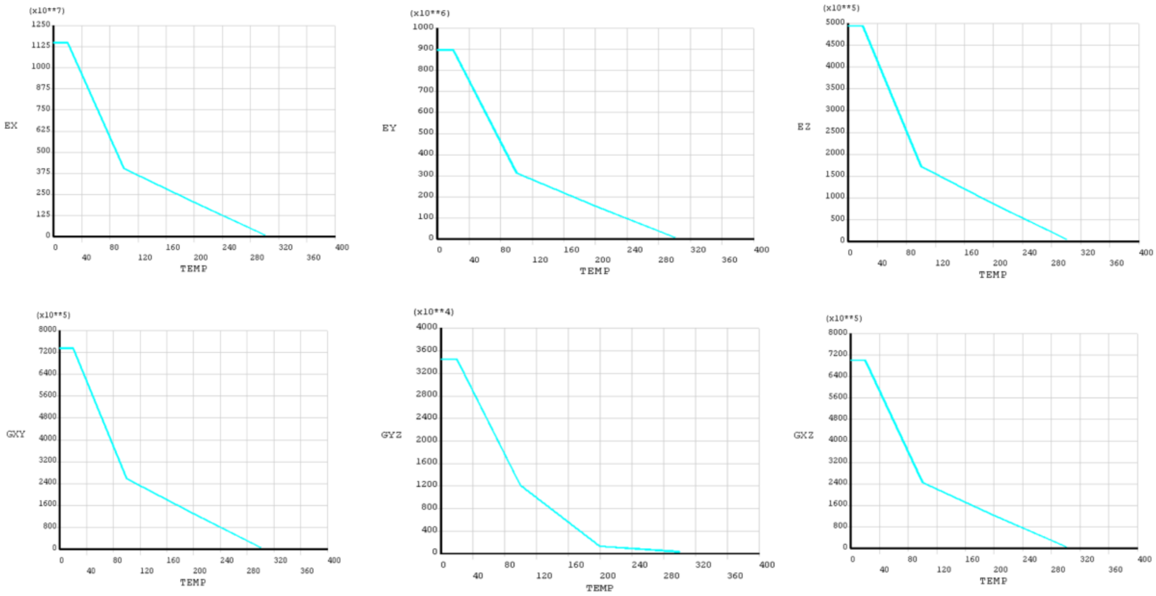


Figure 24: Degradation of orthotropic mechanical properties of wood with temperature

Table 14: Multilinear isotthropropic for the GLT24h

20 ºC		**100 ºC**		**200 ºC**		**300 ºC**	
Strain	Stress	Strain	Stress	Strain	Stress	Strain	Stress
0.0020869	2.4E+7	0.0014907	6E+6	0.0014907	3E+6	0.0020869	2.4E+5

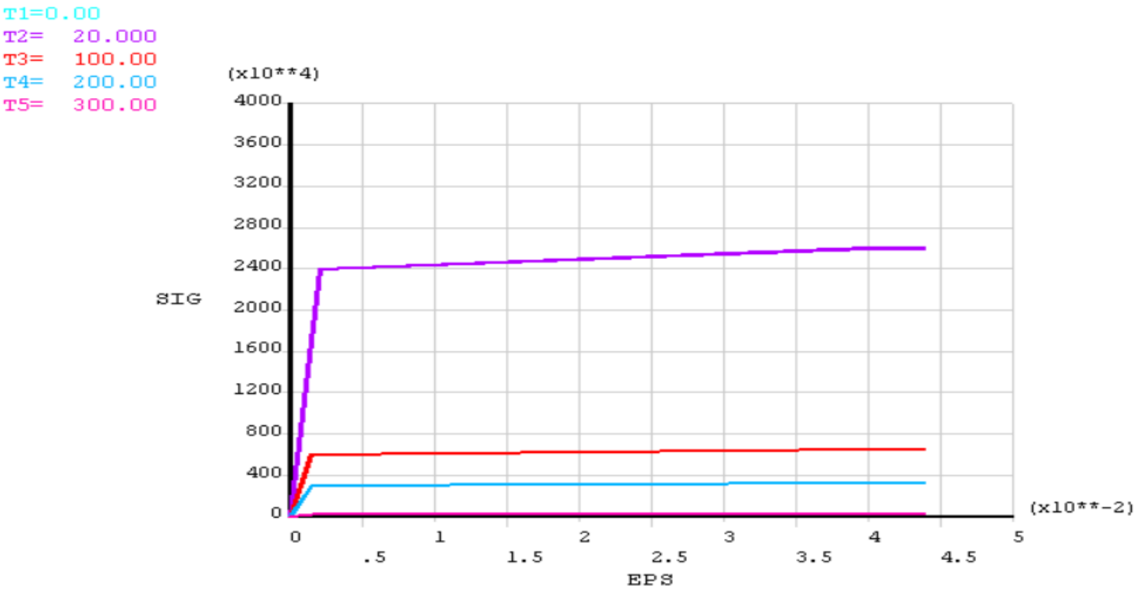


Figure 25: Stress-strain curves of GLT24h

Density

- Timber density: 365 kg/m3
- Gypsum protection layer density: 832 kg/ m3

Creating the Geometry

- Timber Column: Modelled as a rectangular prism with dimensions 100mm×80mmand length 1.3 m.
- Steel Supports: Modelled as cylindrical columns with a diameter of 40 mm.
- Gypsum Protection Layer: A layer of gypsum board, wrapped around the timber column, delays temperature increase in the wood during fire exposure. (12,5mm)

Meshing

The column and support system are meshed using SOLID185 elements for accurate structural analysis, with a denser mesh near areas expected to experience higher stress concentrations.

Applying Nodes and Boundary Conditions

- Nodes are applied along the length and across the cross-section of the timber and steel support.
- Boundary conditions are set to represent fixed support and fire exposure.

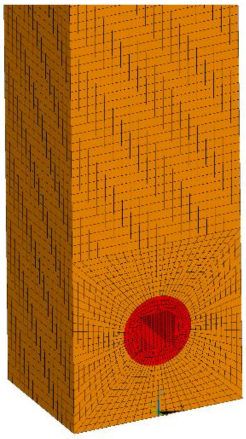


Figure 26: Mesh detail in ANSYS

- The cylinder is supposed to occupy all the space, it is the approach to modelling a very close model that we did in experimental tests.

ANSYS enables detailed structural and thermal analysis, as well as the simulation of advanced materials such as composite wood and high-strength concrete. It supports parametric studies to refine design choices efficiently and can be integrated with BIM platforms to improve coordination across engineering and construction processes.

8.5- Advanced Calculation Method

In this method, a 3D finite element model of a timber column is created in ANSYS, using 5 mm mesh elements for accuracy. The model accounts for the mechanical resistance and thermal effects in both the timber and the gypsum protective layer. The analysis follows three key FEA solutions:

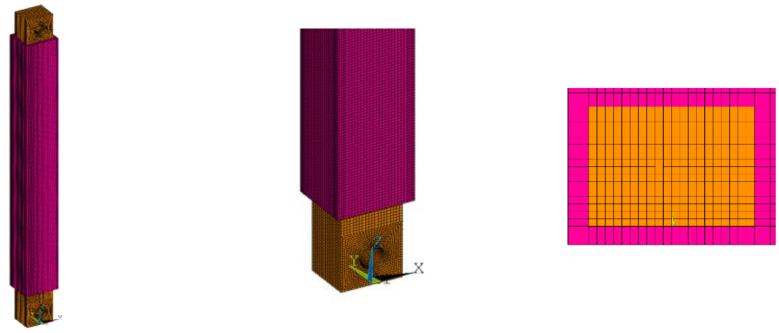


Figure 27: Geometry and cross section (ANSYS)

8.5.1- FEA Solution1: Elastic Buckling Analysis

This first analysis focuses on identifying potential modes of instability within the timber column structure under load. Using the Block Lanczos extraction method, ANSYS calculates the critical load (the maximum load before buckling) and the mode shapes of instability, which help identify weak points for potential failure.

Table 15: Failure Criterion

STRENGTH LIMIT (HILL COEFFICIENTS)					
T (ºC)	0	20	100	200	300
fy	$2.40000.10^{7}$	$2.40000.10^{7}$	$6.0000.10^{6}$	$3.0000.10^{5}$	$2.40000.10^{5}$
T (ºC)	0	20	100	200	300
RXX=RLL=f_{XX}^{Y}/f^{y}	1	1	1	1	1
RYY=RRR=f_{YY}^{Y}/f^{y}	0.052	0.052	0.052	0.052	0.052
RZZ=RTT=f_{ZZ}^{Y}/f^{y}	0.052	0.052	0.052	0.052	0.052
RXY=RLR=$f_{XY}^{Y}/(f^{y}/\sqrt{3})$	0.405	0.405	0.405	0.202	0.179
RYZ=RRT=$f_{YZ}^{Y}/(f^{y}/\sqrt{3})$	0.405	0.405	0.405	0.202	0.179
RXZ=RLT=$f_{XZ}^{Y}/(f^{y}/\sqrt{3})$	0.405	0.405	0.405	0.202	0.179

- Hill Criterion (Constitutive Model): Given that timber is orthotropic, we employ a constitutive model derived from the Hill yield criterion to account for the varying strengths and stiffnesses along each direction of the timber's grain (Ex, Ey, Ez). This model offers a more precise depiction of timber's mechanical strength when subjected to fire-related pressures.

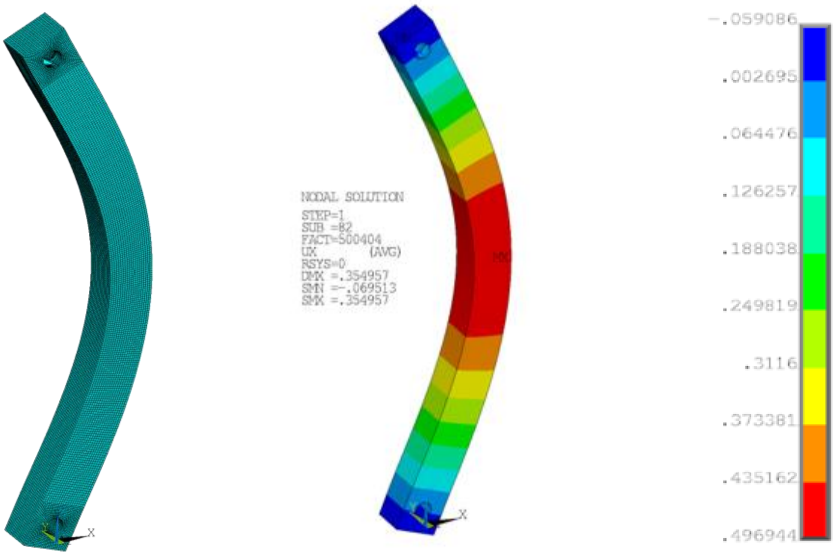


Figure 28: Elastic buckling ANSYS.

- Mode 1: $\lambda = 4{,}60466 \times 10^5$ (ANSYS, File RST)

$F_R = -1\ (N)$

$F_{cr} = \lambda \times F_R = 460466\ \ (\mathrm{N})$

- EULER:

$$F_{cr} = \frac{\pi^2 . E I_{zz}}{{L_b}^2}$$

$$I_{zz} = \frac{bh^3}{12} = \frac{0.08 \times 0.1^3}{12} = 6{,}66 \times 10^{-6}\ (m^4)$$

$$F_{cr} = \frac{\pi^2 .(11 \times 10^9) \times 6.66 \times 10^{-4}}{1.2^2} = 502589\ N$$

- Difference:

$$\frac{502589 - 496944}{502589} = \mathbf{1.12\%}$$

8.5.2- FEA Solution 2: GMNIA

The second analysis, GMNIA (Geometrically and Materially Non-Linear Analysis with Imperfections), combines geometric and material non-linearities with imperfections to assess the structure’s ultimate capacity under fire conditions. This solution calculates the structural response by considering both the progressive degradation in material properties (due to heat) and the deformations caused by imperfections.

  - Incremental and iterative solution:
    - Δt=10 [s], Δt min= 0.0001 [s], Δt max= 10 [s];
    - Convergence criterion: displacement, tolerance=0.001, ref value=1 m
- Geometric Imperfections: The initial mode of instability is used to apply geometric imperfections to the model, considering fabrication and inherent geometric deviations (H/500 for MGL, LVL, H/300H for others) These imperfections provide a realistic initial state for the column, simulating how natural deviations impact stability under load and thermal conditions.
- Mode of instability: (include geometric imperfection)

$$IMP_{max} = \frac{H}{500} = 2.4 \times 10^{-3} m$$

From mode 1:

$U_{x,max} = 0{,}496944m \qquad scale = \frac{0.0024}{0{,}496944} = 4.829 \times 10^{-3}$

$N_{b,rd} = 168204.8(ANSYS)$

$N_{b,rd} = 180871$(EN-1-1)

- Difference:

$$\frac{180871 - 168204.8}{180871} = \mathbf{7\%}$$

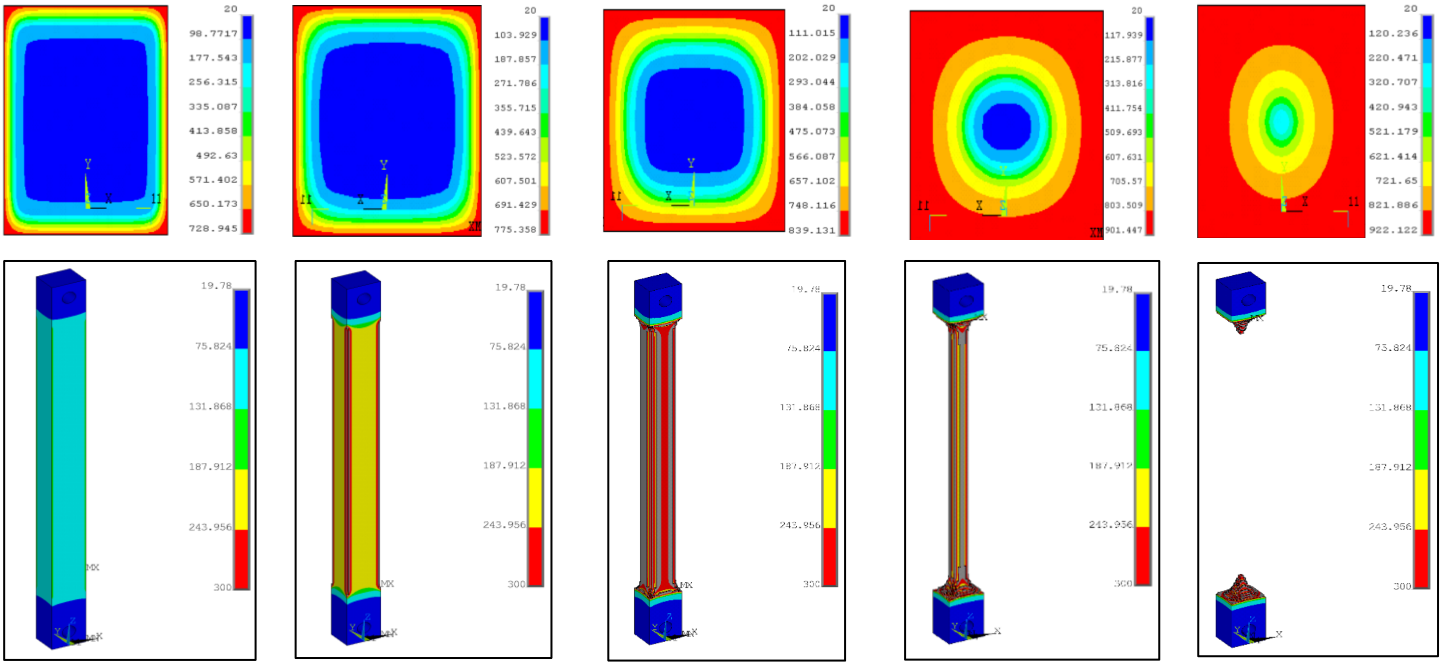
8.5.3- Thermal analysis

In this analysis, the Finite Element Method (FEM) is used to evaluate the charring rate and the residual cross-section of a timber column exposed to fire over time, with a focus on the effect of fire protection. The thermal analysis simulates how heat penetrates both the protective gypsum layer and the timber, influencing temperature distribution, material degradation, and the effective structural section.

Two configurations of fire protection were considered:

- Single-layer protection using 12.5 mm gypsum board
- Double-layer protection using 2 × 12.5 mm gypsum boards

During fire exposure, the timber column's cross-section gradually reduces due to charring. Areas exceeding 300°C are considered structurally ineffective, and the remaining section defines the residual capacity. This thermal analysis is crucial for later mechanical and thermo-mechanical simulations, as it directly influences the column's strength over time.



Time=15 min Time=20 min Time=30 min Time=45 min Time=51,6 min

Figure 29:cross-sectional temperature evolution under fire exposure

8.5.4- Thermo-mechanical analysis

In the final phase of this work, a thermo-mechanical analysis was conducted using ANSYS to evaluate the response of the column under the combined effects of fire and mechanical loading. This step followed three previous simulations: (1) a linear buckling analysis, (2) a GMNIA (Geometrically and Materially Nonlinear Analysis with Imperfections), and (3) a thermal analysis incorporating gypsum-based fire protection. For the thermo-mechanical phase, two fire protection configurations were considered: one layer and two layers of gypsum boards.

To initiate the analysis, the GMNIA simulation folder was duplicated, and the '.RTH' thermal results file generated from the thermal analysis was imported into the new project.

Within ANSYS, load tables were created based on four percentages of the GMNIA reference load (168,204.8 N): 6%, 12%, 21%, and 36%.

The load application was performed on 17 central nodes located on the steel support:

- 15 nodes were loaded according to the full values from each table.
- 2 nodes received half of the respective load values to ensure balanced distribution.

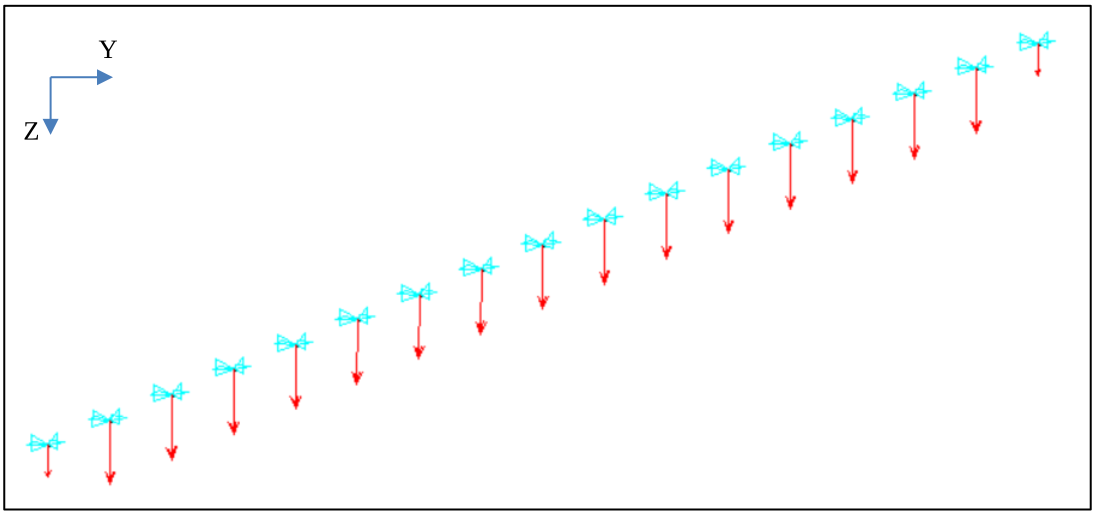


Figure 30: Load applied on nodes

The simulation generated both thermal and mechanical results. On the mechanical side, two types of data were of primary interest:

- Vertical displacement along the Z-axis to assess axial deformation.
- Displacement over time, allowing the observation of the column's progressive response during exposure to thermal analysis

Displacement–time curves and the rate of displacement were studied for both one-layer and two-layer gypsum protections. The results show that adding a second layer of protection reduces how fast the column deforms over time during fire exposure, helping to delay failure and improve fire resistance.

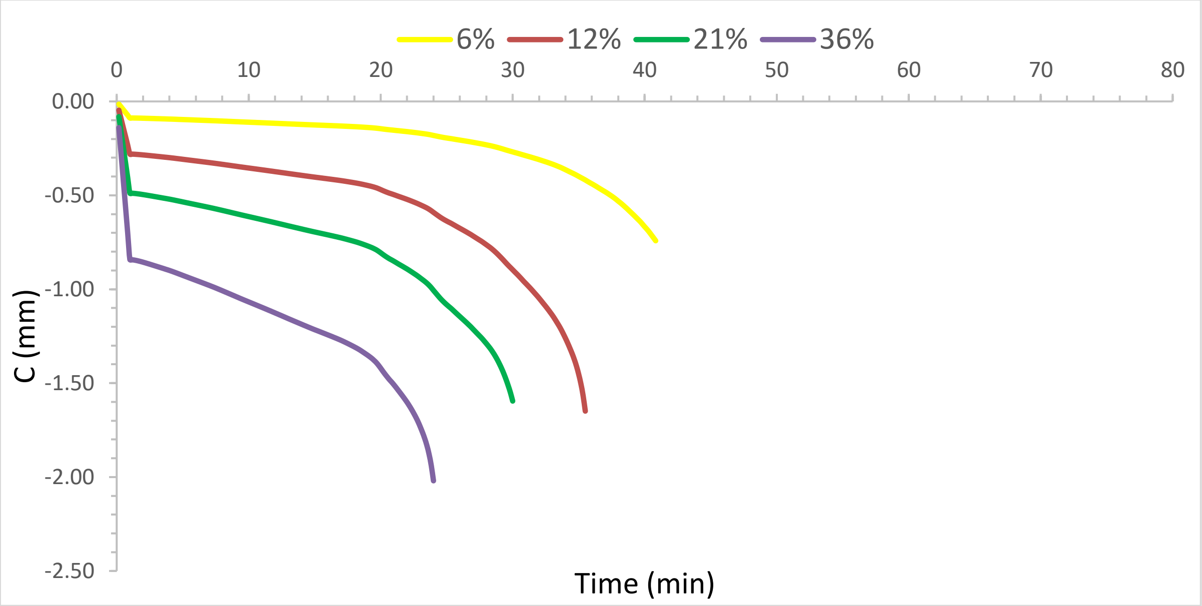


Figure 31: Nodal solution Uz, 1 layer

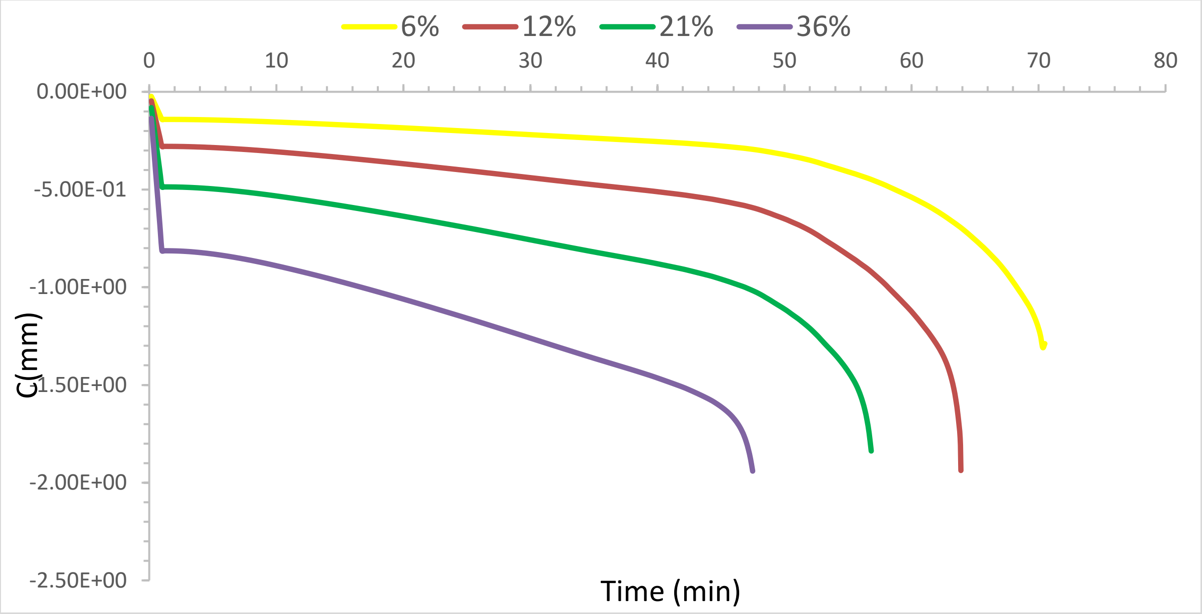


Figure 32: Nodal solution Uz, 2 layers

Those graphs demonstrate that increasing the fire protection thickness from a single 12.5 mm gypsum board to a double 2 × 12.5 mm configuration significantly extends the time before the column reaches critical load levels during fire exposure. At all load percentages (6%, 12%, 21%, and 36%), the double protection delays thermal degradation, proving more effective in maintaining the column's structural capacity over time.

Table 16: Time corresponding to each load

Time (min) Load (N)	Time (min)	
	Simple protected	Double protected
6% = 10092.288	41	70.5
12% = 20184.576	35.83	63.66
21% = 35323.008	30.5	56.83
36% = 60553.728	24.166	47.5

Comparison with experimental results: A comparison between the numerical and experimental displacement–time curves shows strong agreement in the overall behaviour of the column under fire conditions. In the numerical simulation, a load of 35323.008 N (21%) was applied, while the experimental test used a slightly higher load of 36609 N. Both results show a similar deformation pattern, with a gradual increase in displacement followed by a sharp rise indicating failure. The numerical model predicted failure at approximately 30.5 minutes, while the experimental test showed failure around 30 minutes, confirming the accuracy of the simulation in estimating the structural response and time to failure under combined thermal and mechanical loading.

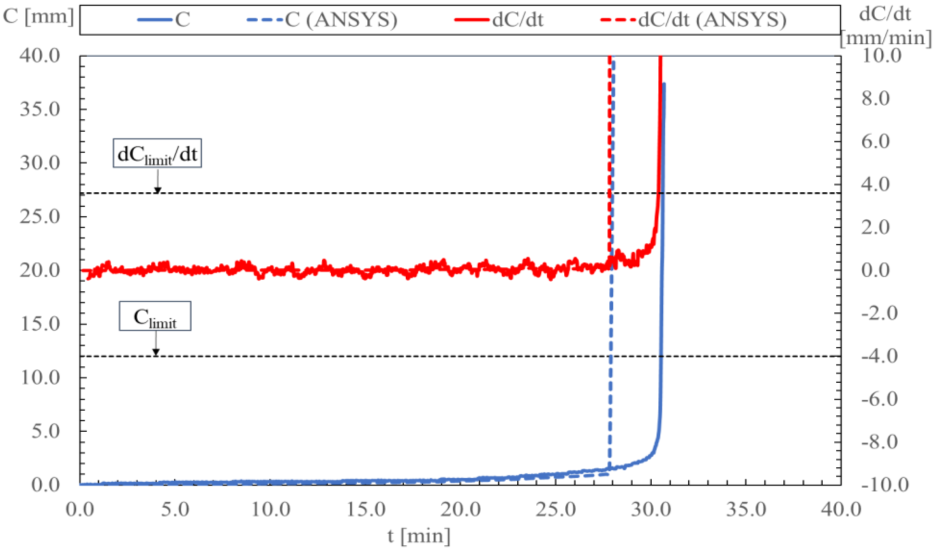


Figure 33: Positive curve of Z displacement

9- Conclusion

The fire resistance of timber columns, whether protected with gypsum or left unprotected, varies significantly based on the solution methods applied. Experimental testing tends to yield higher fire resistance compared to theoretical models, primarily due to the use of realistic material properties and testing conditions. These findings underscore the importance of accurate and comprehensive modelling techniques. The depth of the charred layer remains a crucial factor for evaluating the structural integrity of timber during and after fire exposure. Simplified and advanced solutions sometimes underestimate fire resistance due to assumptions related to GLT bonding behaviour and the inherent properties of wood. Discrepancies between furnace fire curves and theoretical fire curves demonstrate the influence of testing conditions on outcomes, suggesting the need for more consistent and harmonized approaches. While advanced material models offer increased realism, they could be further improved by incorporating detailed composite behaviours unique to timber, such as layer interactions and bonding. Introducing interface elements in simulations would allow for a more accurate representation of real-world conditions, further refining predictive accuracy. Progress in these areas will enhance the development of fire-resilient timber structures.

10- Future Work:

Future research should explore the effects of altering the number of protection layers, such as gypsum boards, to assess their influence on fire resistance under varying thermal loads. Additionally, changing the cross-sectional dimensions of the specimens, including larger or irregularly shaped sections, could provide deeper insights into how geometry impacts the charring rate and structural behaviour during fire exposure. By investigating these parameters, it would be possible to optimize timber designs to achieve better fire performance and enhance the safety of timber-based constructions.

Bibliography

Standards:

EN 1991-1-2. *Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire.* CEN – European Committee for Standardization, Brussels, 2002.

EN 1995-1-2. *Eurocode 5: Design of timber structures – Part 1-2: General – Structural fire design.* CEN – European Committee for Standardization, Brussels, 2004.

EN 1365-4. *Fire resistance tests for loadbearing elements – Part 4: Columns.* CEN – European Committee for Standardization, Brussels, 2000.

EN 1363-1. *Fire resistance tests – Part 1: General Requirements.* CEN – European Committee for Standardization, Brussels, 2020.

EN 13501-2. *Fire classification of construction products and building elements – Part 2: Classification using data from fire resistance tests, excluding ventilation services.* CEN – European Committee for Standardization, Brussels, 2016.

Recent Research (Post-1980)

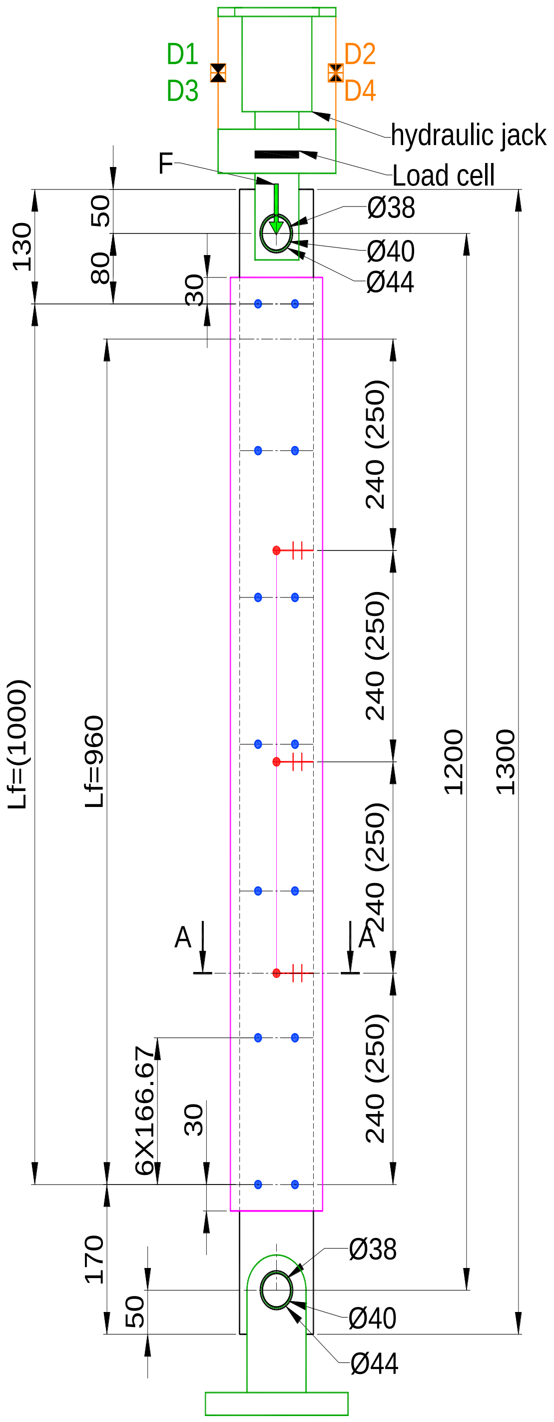
- **[1]** Buchanan, A., & Abu, A. (2003). *Structural Design for Fire Safety*. Chichester: John Wiley & Sons.
- **[2]** Lourenço, L., & Pina, C. (2013). "Performance of timber columns under fire conditions." *Construction and Building Materials*, 47, 785–797.
- **[3]** Görlacher, R. (2016). *Fire Safety Design for Timber Structures*. Berlin: Springer-Verlag.
- **[4]** Keller, T., & Rapp, J. (2020). "Experimental analysis of fire behavior in timber columns." *European Journal of Wood and Wood Products*, 78(4), 623–639.
- **[5]** Clouston, P., & Eastwick, C. (2018). "Timber columns and fire resistance: A review." *Fire Safety Journal*, 99, 45–57.

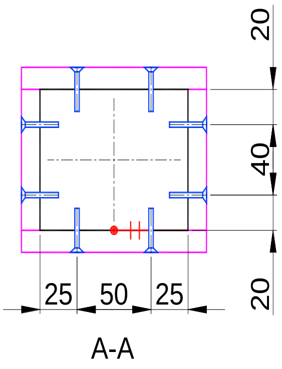
Foundational Research (Pre-1980)

- **[6]** König, J. (1955). "Thermal breakdown of wood: Char as an insulator." *Journal of Wood Science*, 7, 23–34.

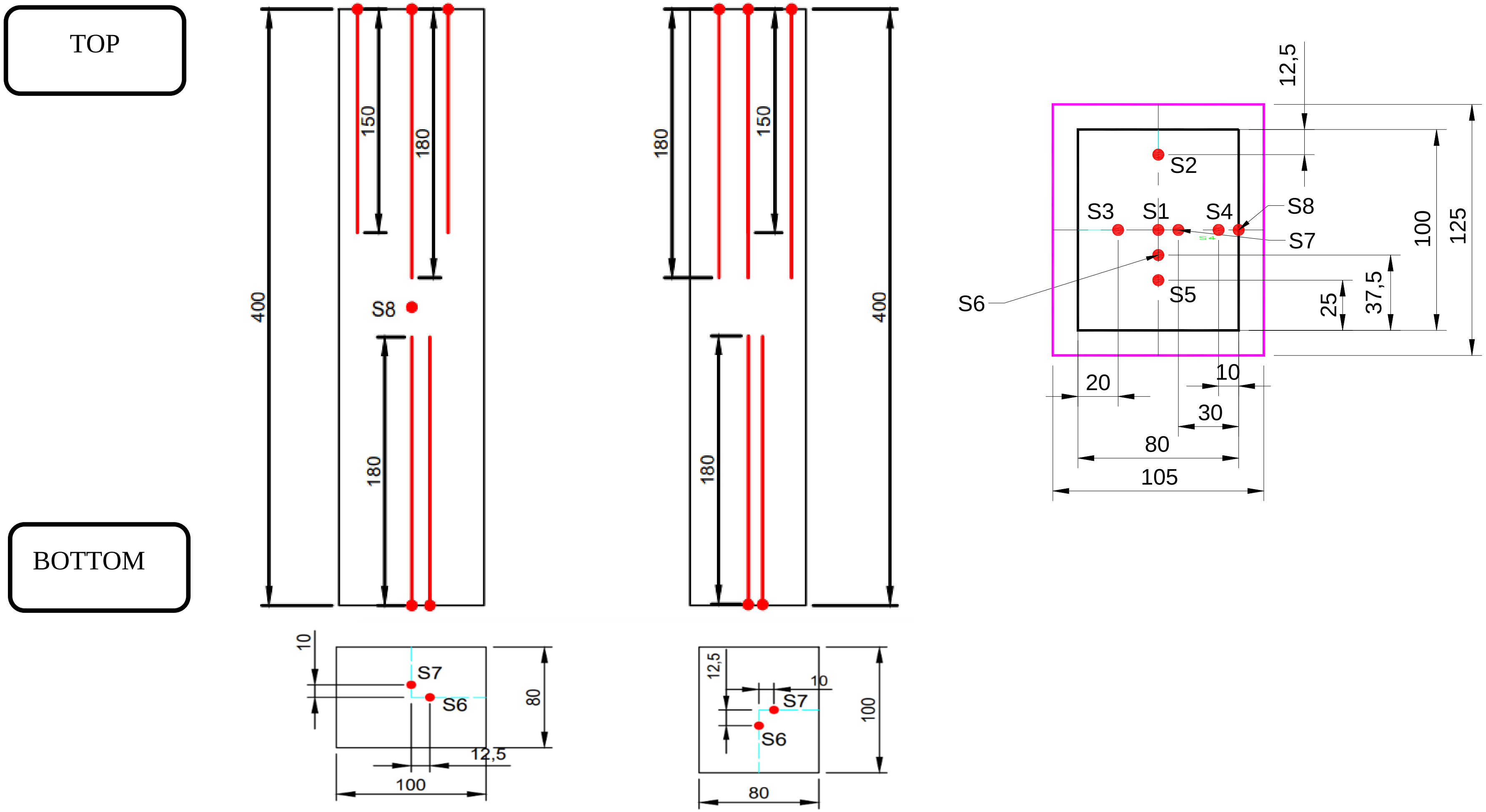
- **[7]** Elliott, R. (1954). "Fire resistance of wooden columns." *Wood Technology Reports*, 5(2), 134–139.
- **[8]** Ingham, H. (1952). "Timber vs. steel and concrete in fire." *Materials and Structures*, 1(1), 10–25.
- **[9]** Fons, W. (1946). "Combustion mechanisms of wood." *Fire Science Review*, 9, 122–131.
- **[10]** Harmathy, T. Z. (1967). "Char's role in insulating unburned wood." *Fire Technology Journal*, 3(1), 29–36.
- **[11]** Lie, T. T. (1967). "Charring rates of heavy timber under fire." *Fire Protection Engineering Research Journal*, 10(2), 45–56.
- **[12]** Saito, Y. (1975). "Heat transfers in timber during fire." *Wood Science and Technology*, 7, 210–220.
- **[13]** Gerhards, C. C. (1979). "Mechanical properties of wood at high temperatures." *Forest Products Journal*, 29(1), 41–47.
- **[14]** Schniewind, A. P. (1970). "Thermal softening and structural weakening of wood." *Journal of Wood Engineering*, 10(3), 180–195.
- **[15]** Buchanan, A., & Cowper, P. (1960s). "Effective residual section in timber columns." *Timber Structures and Fire Safety Research Proceedings*, 12, 11–18.
- **[16]** Furuta, Y., & Furukawa, T. (1970s). "Fire resistance of large timber sections." *Building Science Reports*, 13(4), 85–94.
- **[17]** Schaffer, E. (1966). "Structural resilience of timber in fire." *Wood Research Review*, 5, 23–28.
- **[18]** Fosberg, T., & Marchant, J. (1968). "Gradual charring characteristics of timber." *Materials in Fire Safety*, 12(1), 36–47.
- **[19]** Chowdhury, H., & Hartley, L. (1975). "Axial load behavior of timber in fire." *Fire Safety and Timber Structures Journal*, 8(2), 55–68.
- **[20]** Malhotra, H. L. (1974). "Rates of charring and timber strength." *Fire and Materials*, 5(3), 167–173.
- **[21]** Janssens, M. (1970s). "Charring rates of different wood species." *Journal of Forest Engineering*, 10(1), 50–60.
- **[22]** Beyer, G. (1977). "Fire resistance of glulam timber." *Journal of Engineered Wood Products*, 15, 29–37.
- **[23]** Forest Products Research Laboratory. (1950s–1970s). "Charring rates and fire design codes." *Timber and Fire Safety Technical Bulletins*, 3(6), 1–56.

Appendix 1: Column geometry (ready for test)

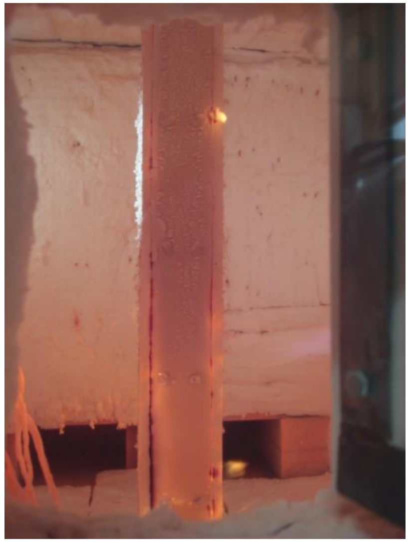


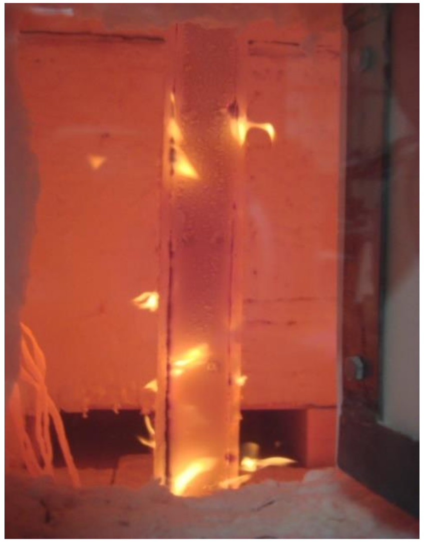


Appendix 2: Dummy geometry (ready for test)

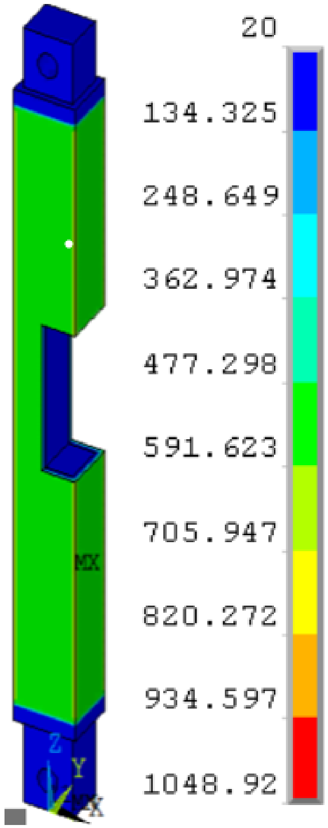


Appendix 3: Specimen Condition during the test

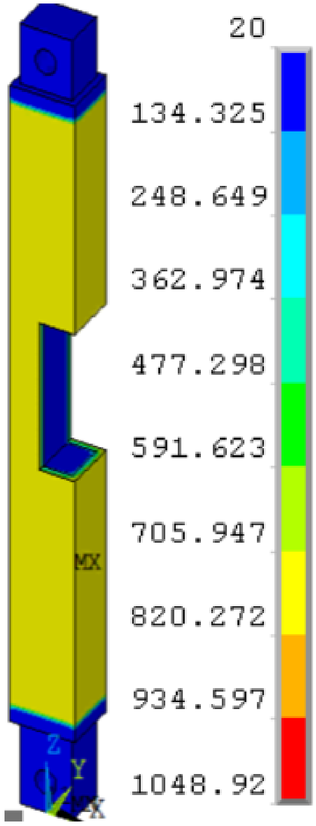




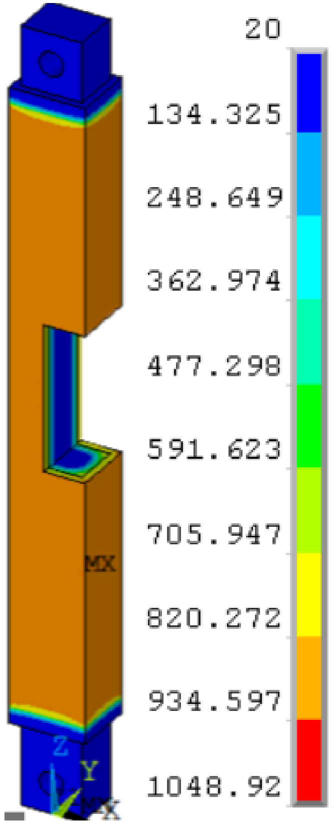
Appendix 4: Thermal analysis (ANSYS)



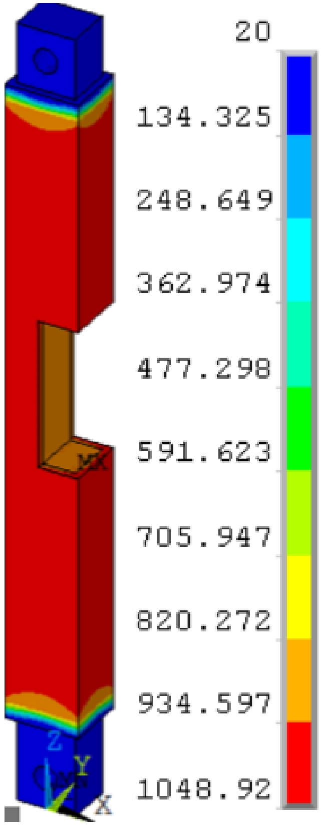
15 min



20 min

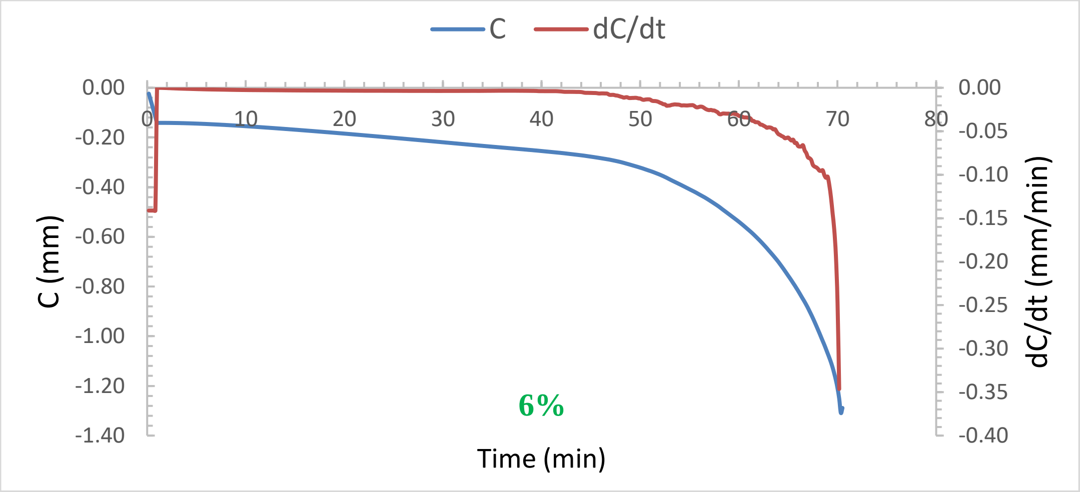


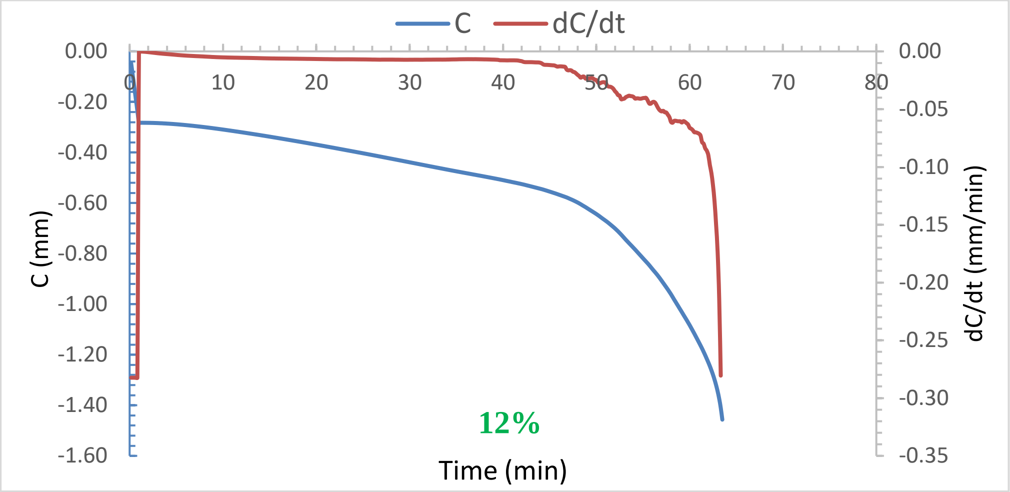
45 min

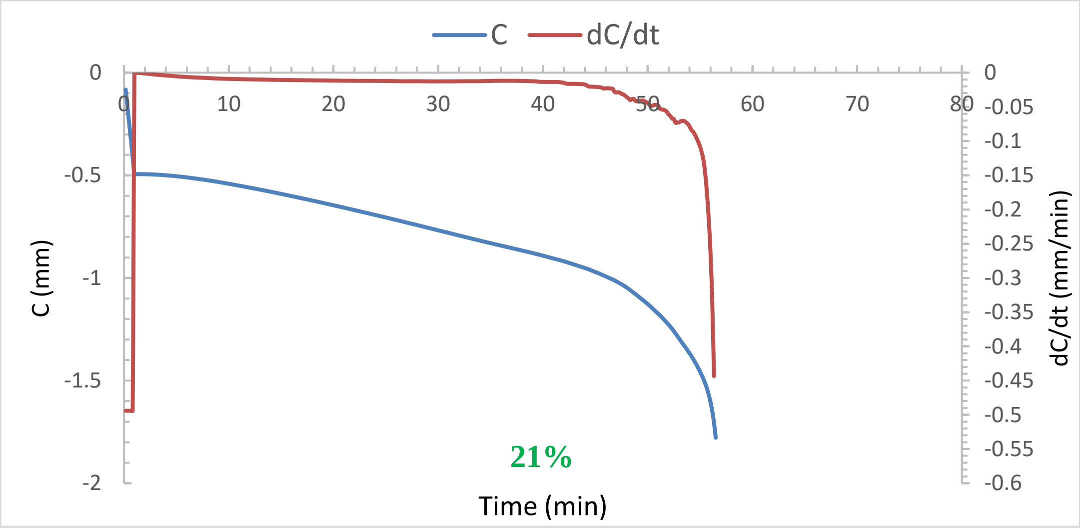


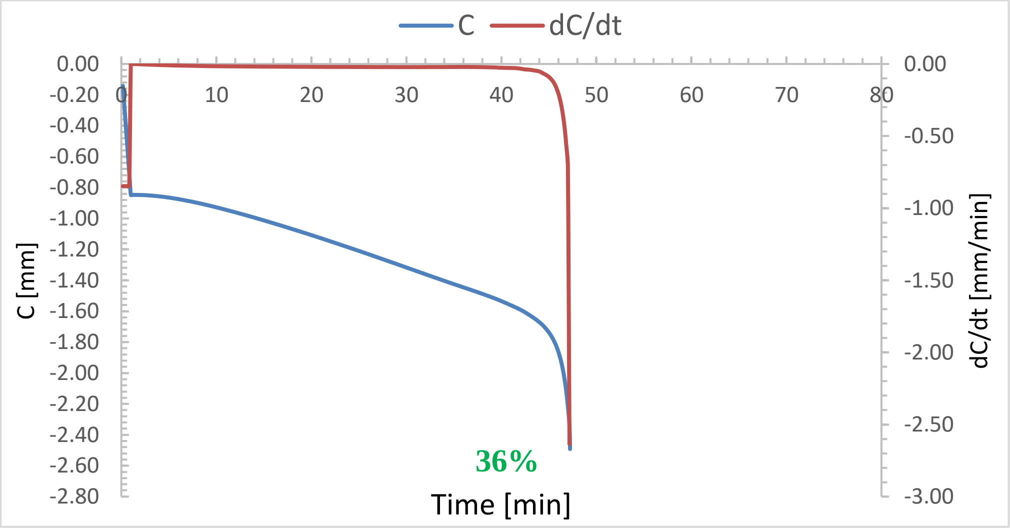
60min +

Appendix 5: Thermo-mechanical analysis 1 layer









Appendix 6: Thermo-mechanical analysis 2 layers