Performance of joints for glued laminated timber exposed to the ISO fire temperature curve

Jesus David Gil Velasquez

Fire safety engineering

Lund university

Sweden

Report 5638, Lund 2021

Master thesis in fire safety engineering

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Report: 5638

ISRN: LUTVDG/TVBB-5638-SE

Number of pages: 79

Illustrations:42

Keywords

Glued laminated Timber, Structural fire engineering, Fire performance, standard ISO fire curve, Joints

Abstract

As society becomes more ecologically conscious there is a push toward the use of materials with a smaller environmental burden, one of these materials is glulam (GLT), which has gained a lot of traction in recent years not only for ecological reasons but for its ease in manufacture, transport, noise dampening, etc.

The focus of this project was to evaluate the influence of different joint configurations on the fire performance of glulam members. To accomplish this 4 different samples were made each with variations in the type of fastener, plates, or protection used; these were fitted with a jack system to simulate the forces that glulam members experience during their use, and were afterwards exposed to 30 minutes of the ISO834 fire curve.

During the time of exposure, the size of the gap was measured as well as the temperature in certain relevant areas of the samples. For the unprotected samples tested the temperatures on the exposed side rose above 800 °C meaning a reduction of more than 90% of their yielding strength by the end of the test. In the case of the protected sample this meant only a 4.39% loss.

Additionally the affected areas were studied to determine the charring rate and burning patterns generated by the specific joint used, for the first joint this charred rate was 1.3±0.1 mm/min, on the second joint 1.16±0.07 mm/min, and 1.23±0.13 mm/min for the third. Finally, the protected joint did not have a measurable amount of charr on the joint itself. In some cases, these charring rates went above from what was expected using the Eurocodes safety factor for joint charring, which was a value of 1.14 mm/min or close to 14 % less than the one obtained in test 1.

The experiments showed the susceptibility of the unprotected joints under high temperatures, significant differences in the behavior depending on the configuration, and the efficacy of fire protection over the mechanical attributes of joints.

Lund 2021.

Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden
http://www.brand.lth.se

HOST UNIVERSITY: Lund University
FACULTY: Faculty of Engineering
DEPARTMENT: Division of Fire Safety Engineering
Academic Year 2020-2021

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Jesus David Gil Velasquez

Promoters:
Bjarne Husted, Lund University

Master thesis submitted in the Erasmus Mundus Study Programme
International Master of Science in Fire Safety Engineering

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4th of May 2021

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Resumen (abstract in Spanish)

A medida que la sociedad se vuelve más consciente ecológicamente, hay un impulso hacia el uso de materiales con una menor carga ambiental, uno de estos materiales es el glulam (GLT), que ha ganado tracción en los últimos años no solo por razones ecológicas sino por su facilidad en fabricación, transporte, amortiguación de ruido, etc.

El objetivo de este proyecto fue evaluar la influencia de diferentes configuraciones de uniones en el comportamiento frente al fuego en miembros de glulam. Para lograr esto se hicieron 4 muestras diferentes, cada una con variaciones en el tipo de conexión, placas o protección utilizada. Estas fueron equipadas con un sistema hidráulico para simular las fuerzas que experimentan los miembros de madera laminada durante su uso, luego fueron expuestas a 30 minutos de la curva de fuego ISO834.

Durante el tiempo de exposición, se midió el tamaño de separación entre vigas y la temperatura en ciertas áreas relevantes de las muestras, para las piezas no protegidas probadas las temperaturas en el lado expuesto se elevaron por encima de los 800 ° C. Esto significó una reducción de más del 90% de su límite elástico al final de la prueba. En el caso de la muestra protegida, esto se tradujo en solo una pérdida del 4,39%.

Además, se estudiaron las áreas afectadas para determinar la tasa de carbonización y los patrones de quemado generados para la articulación específica utilizada, para la primera conexión esta tasa de carbonización fue de 1.3 ± 0.1 mm/min, en la segunda conexión 1.16±0.07 mm/min y 1.23 ± 0,13mm/min para el tercero. Finalmente, la conexión protegida no tenía una cantidad mensurable de carbón. En algunos casos, estas tasas de carbonización superaron lo esperado utilizando el factor de seguridad en los Eurocódigos para la carbonización en conexiones. El cual tuvo un valor de 1.14 mm/min o cerca de 14 % menos que el obtenido durante el primer ensayo.

Los experimentos mostraron la susceptibilidad de las juntas desprotegidas a altas temperaturas, diferencias significativas en el comportamiento según la configuración y la eficacia de la protección contra incendios sobre los atributos mecánicos de las juntas.

Acknowledgments

The results of this work could not have been done without the support of several individuals, and to all of them I would like to express my gratitude.

Most specifically I would like to thank all the people at the Danish institute of fire security and technology (DBI) as they provided all the equipment and expertise to perform the experimentation within this report, also their support and interest in this work made significative contributions that are too numerous to mention.

On a personal note I would also thank my supervisor Bjarne Husted who had to cope with many emails and questions during the making of this thesis, as well as Alexandru Radulescu and Dan Lauridsen who provided tons of help during the experimentation.

Finally, and not least important I would like to thank all the people that are involved in the IMFSE program since without them the making of this thesis would have been impossible.

Table of Contents

List of abbreviations

GLT	Glued laminated timber / Glulam
ISO	International organization for standardization
EN	European standards
RCSM	Reduced cross section method
EYM	European yield model

List of figures

List of tables

1 Introduction

1.1 Background

Engineered timber products have being taking a spotlight as materials with a smaller impact on the environment when compared to more conventional construction materials such as steel or concrete, while providing a myriad of attractive properties such as great esthetics, fast assembly, good insulation to sound and heat , etc.

One of these engineered products is Glued laminated timber (GLT or Glulam). It consists of a layer or layers of solid timber boards glued together to increase their mechanical performance. This increase plus the possibility of creating pieces of any dimension has made the material a more fitting choice for large wooden structures[1].

An advantage of GLT over some other structural materials is that it allows the creation of custom made columns or beams that can carry loads in a more effective manner than common structural timber, and in this way reduce the amount of additional structures that could increase the cost of a design [2].

In order to make use of this ability connections are established to distribute the loads across different structural members. Depending on the type of connection and mechanical requirements several types of joints can be used, as well as nails, brackets, plates , etc [3].

Glulam was first introduced in Europe in 1906 as a novel way to create solid timber pieces with custom shapes [4] and since then its use has expanded in several countries where it has been one of the main constituents in tall timber structures.

The adoption of this material however has been slowed down in certain regions due to the combustible nature of it, none the less, the implementation of more performance based designs and ease in regulations in certain areas has pushed its use even in high rise buildings[5].

This does not mean that these new timber structures are unsafe, on the contrary, the legislators have made sure that designers and engineers would provide an equal amount of safety for these timber structure to those building made with more conventional materials. To do this it is of the upmost importance to understand the behavior of timber products in normal use as well in a fire scenario.

To measure the performance of glued laminated timber several studies have been made, these tests have covered several aspects both in cold and fire conditions, such as charring rate, delamination, influence of adhesives used, mechanical behavior under certain stresses etc. And is with these tests that engineers and designers can have an idea on how a building will perform once its finished.

But as was mentioned before one of the main components needed to create GLT structures are joints. Although there have been several studies covering the behavior of joints in Glulam in cold conditions there is a limited amount of information regarding jointed glued laminated timber under fire conditions.

In order to reduce the risk of failure at the joints at high temperatures it has become common place to protect exposed joints with additional material or to conceal the connections inside the GLT members, none the less since these two methods require more material and more labor it is also possible to observe exposed connections in some structures[6].

Since a design will fail at its weakest link it seems imperative to evaluate the behavior of such systems and examine the impact of a fire on its structural properties.

1.2 Purpose & objectives

The goal of this work is to further the understanding in GLT-joint systems when exposed to a standardized fire curve.

Once this is executed the test samples will be analyzed in order to draw meaningful data that could prove useful when designing a GLT structure.

The objectives that will be investigated are:

- Observe and record the behavior of several GLT to joint systems when exposed to a load and the ISO fire curve
- Study the mechanisms of failure in the system, and provide information regarding the main sources of it (charring, reduction in the strength in the connections, etc.)
- Provide information on the effects produced by the change of some parameters (size of connection, distribution of joints, type, etc.) on the behavior of GLT to joint systems when exposed to high temperatures
- Using the collected data to provide recommendations that could improve the fire behavior of buildings using GLT.

1.3 Limitations

Since this work will be mostly experimental, the results from it will be restricted by the availability of resources, availability of the testing facilities and time. Some more specific limitations can be seen below.

- Testing will be done using a mobile oven with an aperture of only 50 by 50 cm so only a small area can be exposed to the fire curve, meaning that the results will focus only in a small area surrounding the joints.
- Due to the high variability of joints and GLT it will not be possible to provide information on all possible configurations of GLT-joints assemblies.
- Since the experiments will be done in Denmark borders issues may cause limitations on the amount of testing
- The limitations on the amount of testing could provide difficulties in ensuring that the results are accurate

1.4 Methodology

The project will be structured in the following way:

1. **Literature research**: for this section a comprehensive analysis on the properties of GLT will be discussed as well as their behavior in fire, following this the behavior of joints for timber products in cold and in fire conditions will be covered.

2. **Experiment design**: experiments on GLT-joint systems will be designed according to the available resources and the previous stated motivations, these experiments will be done in a mobile oven provided by the Danish institute of fire and security technology, and each joint will be exposed to the ISO fire curve and a mechanical load.

3. **Experiment execution**: the GLT and joint assemblies will be built and tested using the design from the previous step

4. **Analysis of results**: once the experimentation is done, the data will be tabulated and analyzed in order to provide meaningful results

2 Literature study

The main purpose of this chapter is to provide enough theorical background to have the necessary information to understand the possible results of this work and their implication on the fire design of Glulam structures.

First the characteristics of timber in general will be discussed, afterward a brief summary on the mechanical characteristics of Glued laminated timber will be shown as well as the behavior of this material under high temperatures.

Additionally, the last section on this chapter will focus on joints both in cold and fire conditions.

To complete this literature survey, three books were used as the main source of information Glulam Handbook Volume 1[1] , Materials and Joints in Timber Structures [7], and CLT Handbook: cross-laminated timber [6]. The information provided by them was then complemented with some of the references mentioned by those books as well as several research papers found through various scientific journals.

2.1 The characteristics of timber

Wood has been a present in nature for millions of years and is the result of the adaptation of plants to certain environments with specific characteristics. Since its conception was directed by adaptability this means that wood has a great variability when it comes to strength, elasticity, density, and color[8].

This will not only depend on the species of tree that produced it but also on the circumstances of the environment where it grew, due to this variability it is impossible to assign a fixed value for certain properties to a particular type of timber, none the less, a range of expected attributes can be assigned to the timber produced by a particular species.

No matter the specific type of timber they all share the same building blocks, cellulose, hemicellulose, lignin and small amounts of extraneous materials [9]. The cellulose as well as the hemicellulose are low molecular weight polymers that give timber products their characteristic fibrous behavior.

These fibers travel in the same axis of the plants growth and are the main source of mechanical strength in timber, since these fiber travel mostly in one direction this makes conventional wood products an anisotropic material, meaning that the strength in most lumber products will depend on the direction in which a force is exerted [9].

The variability in the proportion of these building blocks and the way they are arranged will be the main differentiator in the properties of timber, cellulose will act as a structure that will hold the cell walls while lining and hemicellulose that have a less crystalline structure will act as a bond between the cellulose chains [10].

It is hard to assign a mechanical value on wood just by knowing the percentage of these components, since the mechanical performance will also be affected by the size of cells, orientation of the fibers, size of these fiber, moisture content, copolymerization etc.

Due to the mechanical attributes and the ease of access of the material in nature, wood has been used extensively as a construction material, most of it comes in the form of standard light weight timber members used to assemble frames and roofing. The innate properties of timber allow for a fast installation without requirements for complex machinery which has made it a great material to create small to medium buildings[11].

However, the natural limitations in strength in various axis, possible sizes of members and pricing has led to the adoption of newer engineered timber products for larger or more complex designs.

Engineered timber products or wood composites are made by joining boards, strands, layers, or particles of lumber, these products can possess several advantages over regular lumber depending on their manufacture such as[12]:

- It allows the use of smaller trees: by using an adhesive to join the material the dimensions of the fabricated pieces are not limited to the size of the tree from where the wood was harvested
- Creates a more consistent material: by amalgamating pieces from different sections of various trees and imbed them together within a matrix is possible to generate more predictable properties than those present in solid timber beams
- Diminishes the amount of defects present: since timber is a natural material it can contain defects such as knots that could reduce the viability of its use in certain circumstances, during the manufacture of engineered timber a pre selection process can be used and those defects can be then discarded
- Increase in strength: since lumber is an anisotropic material it means that it will have a weak and a strong axis when confronted with a load, in composites this anisotropy can be reduced by layering the material in various directions allowing for a stronger material.

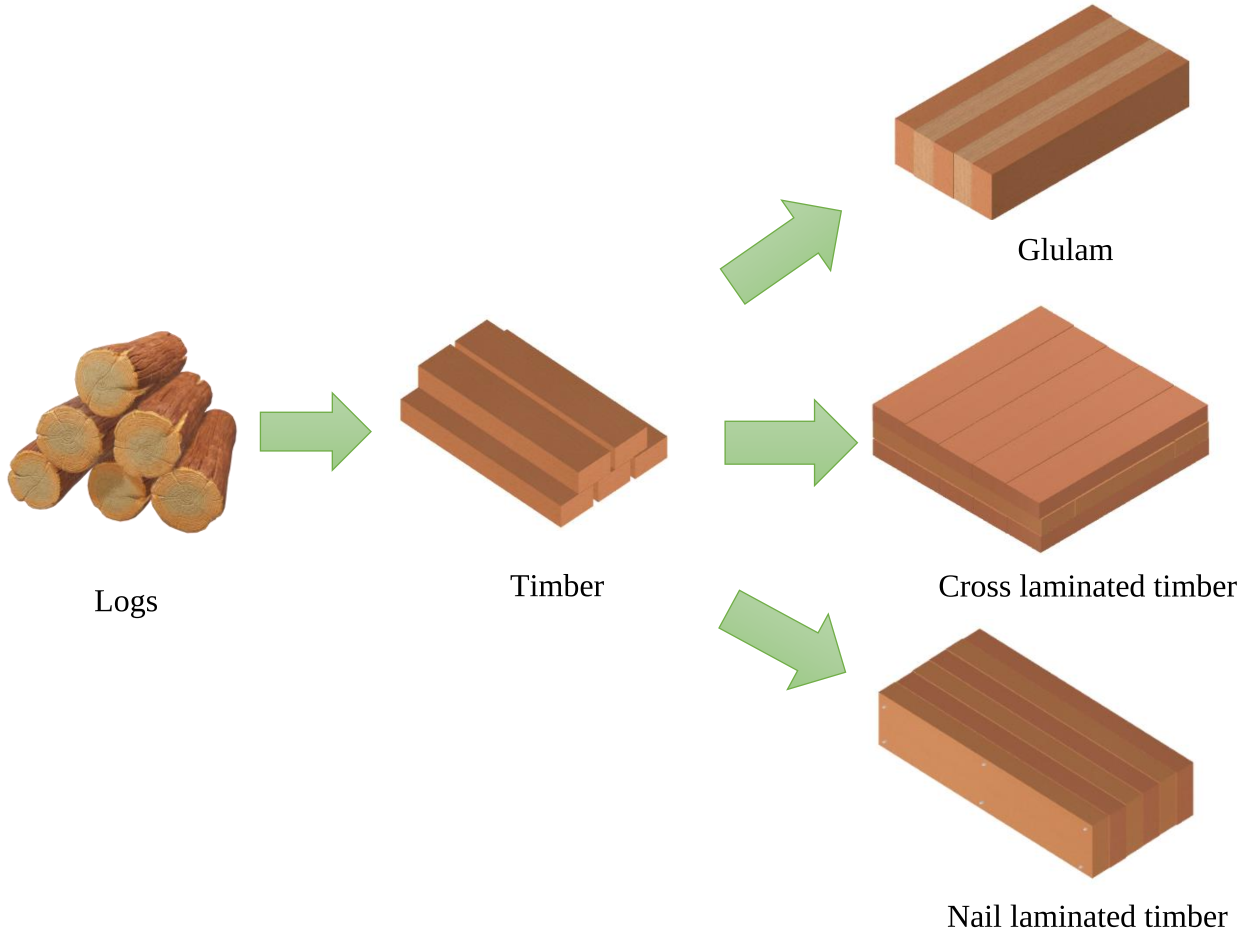


Figure 1.Timber processing and different laminated timber products (glulam, CLT and nail laminated timber) inspired by [13]

As is shown in the figure above changes in the processing of the wood will generate different products depending on their manufacture, the three examples shown, glulam, cross laminated timber, and nail laminated timber have as a main component planed, cut and dried timber pieces joined together; how these pieces are attached together is what leads to most of the variations between each material, for the nail laminated timber the boards are placed with the grain parallel to each other and unified with nails, this method is used to improve the mechanical properties of low to medium grade timber at a low cost[14].

On the other hand Cross laminated timber is a layered wood product composed of boards or lamellae that are jointed together with an adhesive and then bonded together at an angle of 90˚ between layers, this arrangement allows it to bear in and out plane loads as well as provides it with a high dimensional stability [15].

Glulam which will be the main focus of this document, will have a more in-depth description of its properties in the next section.

2.2 Glued laminated timber

To understand the behavior of GLT systems we will focus this segment on a summary of what glued laminated timber is, its mechanical behavior under standard conditions and finally its reaction towards fire.

2.2.1 Main characteristics of Glued laminated timber

Like other timber based material GLT shows an excellent medium for heat and noise insulation, stability against vibrations produced by seismic activity, rapid assembly and carbon sequestration [16].

In the last section we discussed that one of the possible benefits of engineered timber products is the option of creating structural member with large or custom dimensions, this is not different for GLT, the adaptability offered by this product has allowed the creation of prebuild custom pieces that can ship pre-built and be assembled in situ quickly.

Due to all of these properties is clear why the use of this materials has become more common place in the building sector, and why it is one of the main building blocks for tall timber buildings such as the Brock Commons Tall wood house in Canada[17].

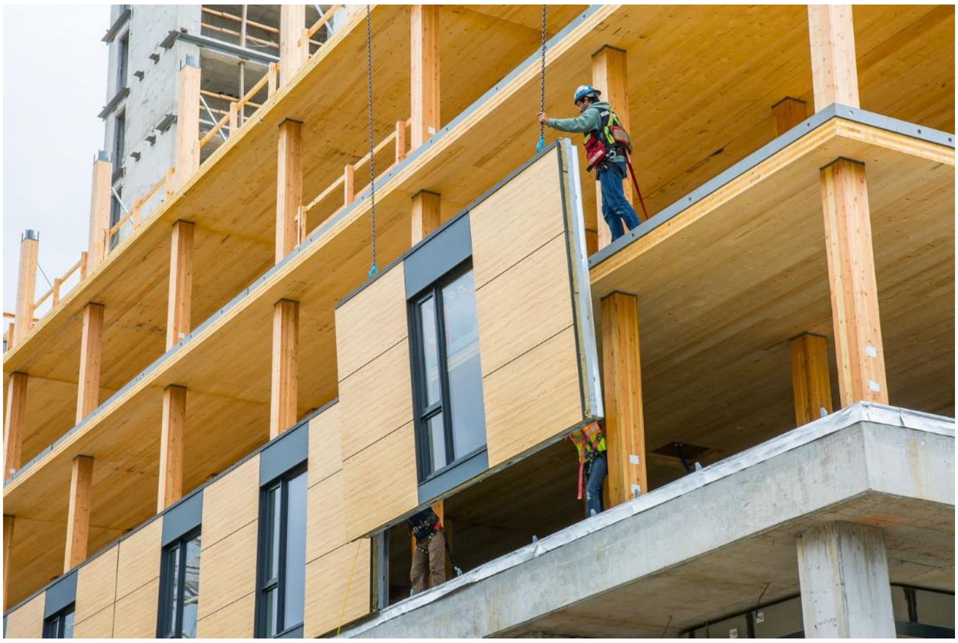


Figure 2.Brock Commons Tallwood house during construction, showing glulam columns [18]

Due to the variable nature of the main component of GLT, and its current role as a structural component, its definition and attributes are encompassed and controlled either by national regulations or international standards, an example of this is EN14080 [19], by this norm for a timber product to be considered Glued laminated timber must follow the next specifications:

- Be made of poplar, spruce, or other relevant species
- Built with a minimum of 2 parallel bonded layers
- Have lamellas with a thickness between 6 to 45 mm
- Jointed by either phenolic, aminoplastic, PUR or EPI adhesives
- Meet the mechanical, environmental and safety standards set up by any other relevant European regulation

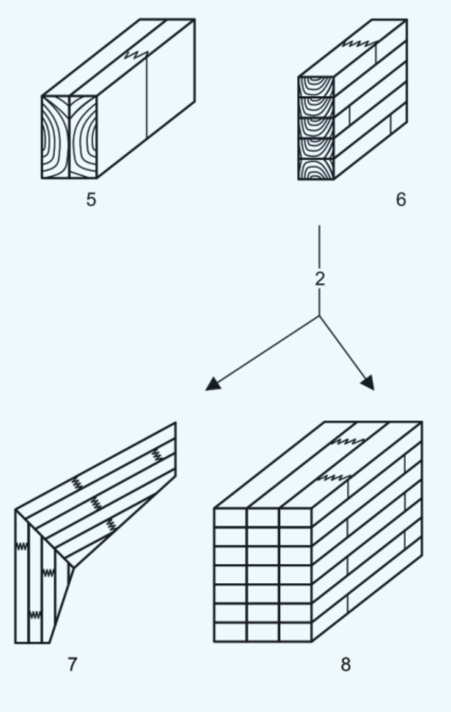


Figure 3.Different configurations for a Glulam member as per EN14080[19]

2.2.2 Mechanical behavior of Glulam

Although the regulations do possess certain values of mechanical requirements for GLT structures to meet, these values are often within a range, the fact that Glulam can be manufactured with different types of boards, adhesives and bonding methods can cause variations that can result critical when designing. These mechanical requirements are vital when it comes to the creation of any construction, as the structural members depending of their function will have to handle a mix of, tensile, compression, bending and shearing loads at any given time[1], an image showing a depiction of these forces over a member of a different timber product (CLT) is showed below.

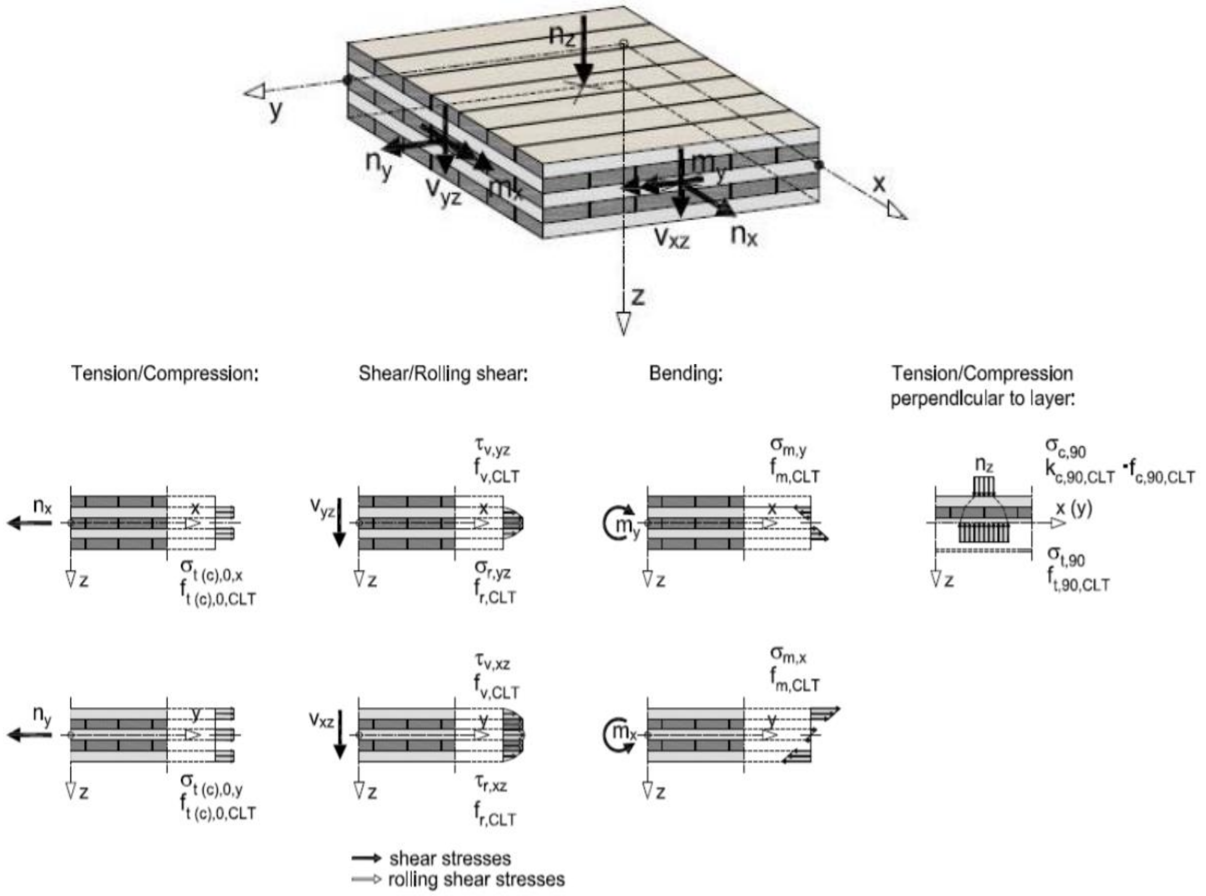


Figure 4.Applicable loads for a structural member of CLT [20]

In Figure 4 a CLT member is showed with different loads (denoted by black arrows) in distinct sections showing the various influences of the forces on the resulting stresses. From this, one can see that for some engineered timber products the effects produced are not as simple to define as in conventional timber elements, due to the variable nature of their composition; in the case of glulam some of this characteristics will be described below.

Bending strength is a rather significant aspect when it comes to define the characteristics of GLT, so much so that the material is sometimes classified by its performance in bending, for example glulam samples can be classified as a GL 28h or GL 28c category, where GL refers to glued laminated, the number refers to the characteristic bending strength (in MPa) ,and h and c refer whether the material is homogeneous (using timber with the same strength classification) or combined (using timber with different grades or from different species)[21].

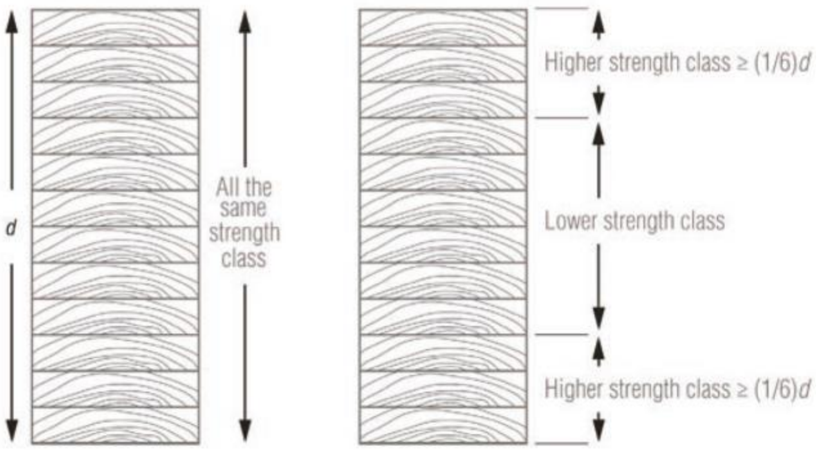


Figure 5.Representation of a homogeneous (left) and a combined glulam member (right) [22]

For combined pieces of glulam is common to put the most mechanically resistant pieces in the more outmost parts, as these pieces will be the ones exposed to higher loads when a shearing force is applied. How resilient to bending a piece is will depend on several aspects such as their composition, building process and orientation [22]. A way to calculate the bending properties of a profile is to use the methods present in the Eurocode 5 [23].

The tension properties of GLT are dependent on the orientation of the fibers within the member in respect to the force in tension, as fibers parallel to the force in tension will provide more strength out of a given section[24].

Another aspect that is critical for the strength in tension of a member is their degree of lamination, a higher degree of lamination (more layers of timber) will by proportion have less natural defects (knots, cracks, curvature of the grain, etc.). Since these defects are often weak points during a tensile stress, this means a reduction in the strength of the material for those with a smaller degree of lamination[25].

An additional important factor when designing a building is the shear strength, once a building is in service it is expected to have certain bending due to in and out of plane loads, there have been several studies trying to determine the resistance of the material and the influence of parameters such as the type of boards used and their geometry[26].

For layered engineered timber products there are three main types of in-plane shear mechanisms that could occur and cause a failure, net-shear, in which there is shearing perpendicular to the grain of the cross section, torsion which happens due to the failure on the bonding layers, and gross shear, where the failure occurs parallel to the grain of the GLT member [27]; as for the out of plane there are two types of failure mode shear and rolling shear[28].

How well the material copes with these failure mechanisms will largely depend on certain characteristics such as the proportion of earlywood within the boards, quantity of knots present, layer width, layer thickness and the size of the gap between boards. These factors makes the determination of the overall shear resistance for a GLT system a more complex endeavor that for some other components[29].

The last of the loads from which Glulam member could be affected by is compression, and since a big part of the use of this material is as structural columns it must be taken into consideration when designing. Just like for tension, the orientation of the fibers is decisive in the behavior of the member, for a compression force parallel to the fiber the resistance of the member will be higher than the strength of the material perpendicularly. During a perpendicular compressive load, the tubular cells that form the wood are compressed and can be permanently deformed leaving cracks or deformation [30] [11].

2.2.3 Fire behavior of GLT

Most fire designs for building are based on predicting the load bearing abilities of any member after being affected to high temperatures for a certain amount of time, and making sure that the structural capabilities are maintained for enough time as to assure the safety of the people within it, or ensuring certain amount of property protection.

For GLT this approach is also taken, much like wood, glued laminated timber goes through a series of physical and chemical phenomena when exposed to a fire, first the material heats enough to evaporate some of the water contained in it, after this the material will start to go through a thermal decomposition and pyrolyzing creating flammable gases as well as producing a charred layer on the affected surface. This char layer offers the unaffected timber some protection towards the fire but provides almost no structural integrity towards loads, meaning that the mechanical properties of the element will degrade the more timber is pyrolyzed[31].

Unlike for regular timber the presence of an adhesive can alter the behavior in regards to a fire, this adhesives can soften, or burn under high temperatures and create weak points within the lamellas of the glulam, this can cause a phenomena called delamination, where the timber members from which they are composed start to detach from one another compromising the structure. This has another impact in the fire behavior, the falling of the charred layer, when this happens the positive effects of the protection are reduced and more fuel is exposed to the fire[32].

Even though GLT member do possess this dissimilarity the methodology for their design in fire conditions is based on the same concepts of other wood products, this concept is the existence of layer of charred product, a heated timber layer that is not considered in any mechanical endeavors and a timber layer that maintains it normal properties, how these layers change with time will depend on the interactions of the fire or heat source with the wood product, but it is common place to simplify this behavior into a steady charring rate that can be used to calculate how much unaffected material there is at any given moment[33].

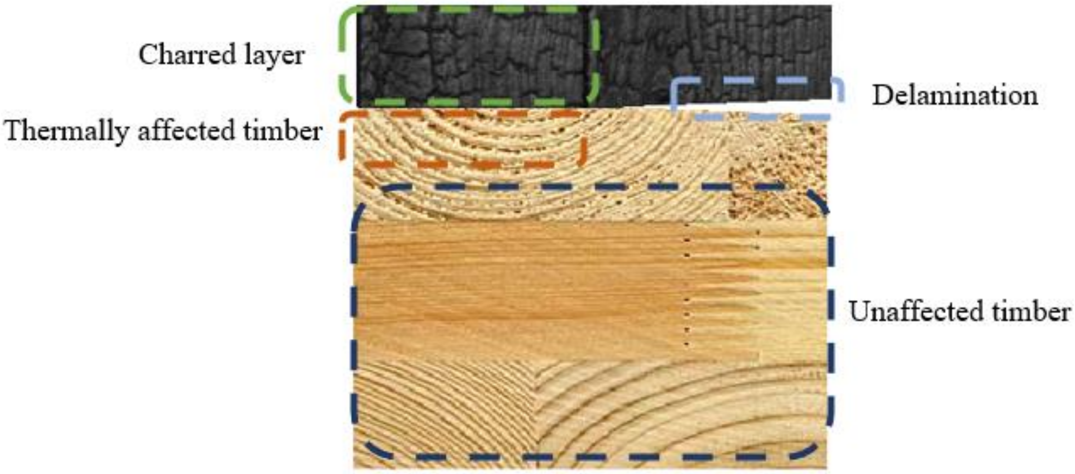


Figure 6.Different zones in a timber member exposed to a fire inspired by [34]

Knowing the charring rate of the material is then possible to use a technique displayed in the Eurocodes called the reduced cross section method (RCSM), this technique is based on what was previously mentioned on the existence of various different layers affected by the fire.

First the char layer dept is calculated at a time using the charring rate, the thickness of this layer is then added an additional 7 mm that represent a layer of lumber that has zero strength, these 7 mm come from previous models on glulam [35], the area of the zone without strength is then deducted to the total area of the member and its remaining strength is then calculated.

By knowing the remaining strength, designers can build over dimensioned structures that will possess the necessary strength even after a fire has occurred, is worth it to mention that new studies have put some doubt the validity of RCSM for other timber products such as glulam or CLT [35].

One of the reasons some doubts have been casted for this method is the variability on charring rates in different timber products depending on their density, humidity, permeability etc. These factors are not necessarily defined by each type of timber as different growing, processing, storing conditions and grain orientation during their use can affect these properties. A rule of the thumb relates denser, more humid and less permeable materials to lower charring rates [36].

For glued laminated timber the charring rate is often taken as 0.7mm/min[33], but is worth to mention that the burning behaviors will depend on the configuration between the timber and the adhesive, for example another engineered timber product (CLT) with larger thicknesses of layers showed charring rates of around 0.65mm/min while the same material with thin layers showed an increase to 1.0mm/min, this increase is caused by the continuous involvement of several adhesive layers making the members act more like a panel [37] .

Another factor that affect this charring rate is the grain orientation in regards to the fire, as we said before permeability is an important factor when it comes to finding the charring rate, a grain oriented to the same direction to the fire will mean more heat permeating trough the material and an faster creation of pyrolysis products [38].

It should also be stated that the charring rates previously specified are taking into consideration a standard fire curve, for most of them the ISO 834 or the ASTM E119 [39]. Unlike a regular fire with a growth phase, a fully developed fire and a decay phase; the fire curves in the norms follow a standardized pattern, in case of the ISO 834 this pattern is defined by the equation shown below.

$$T_g = 20 + 345log_{10}(8t + 1)$$

Where:

T_g: the temperature at any given time in Celsius

t : the time in minutes

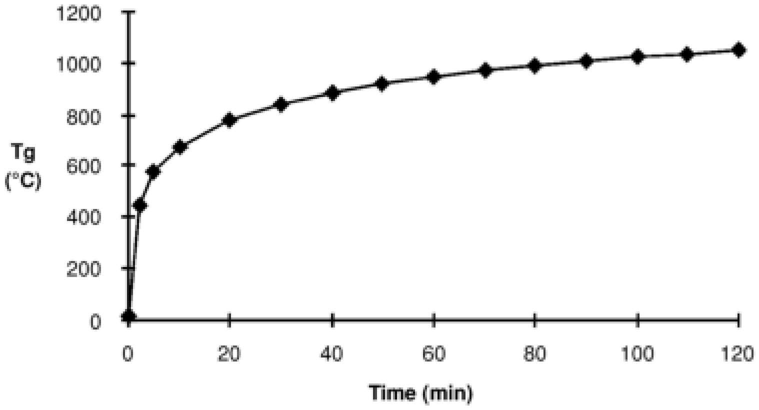


Figure 7.ISO 834 standard temperature-time curve[40]

By observing this equation is possible to see that the temperature in which a member is exposed does not take into consideration the geometry of the enclosure, fuel loads, different ventilation configurations or other factors that could have an effect on the temperatures observed in a real fire[40]. So, although this curve does provide some information in regards to the reactions of a structural member under high temperatures the results produced by it do not take into consideration some nuances that could most likely change the expected behavior under a real fire.

A natural fire will have a growth phase, a fully developed stage and finally it will decay; this is not the case for the standard fire curve, in which the temperature only keeps on growing. This difference can mean under the right circumstances an underestimation or over estimation of the actual fire resistance [41].

In the picture below some natural fire curves are compared to the ISO 834, for the first minutes one of the natural fires surpasses the temperatures provided by the standard. However, once the decay phase starts to set in, the behavior of the standard fire curve becomes the most severe. This shows some of the difficulties present when comparing the results of a standardized test and the results of an actual fire.

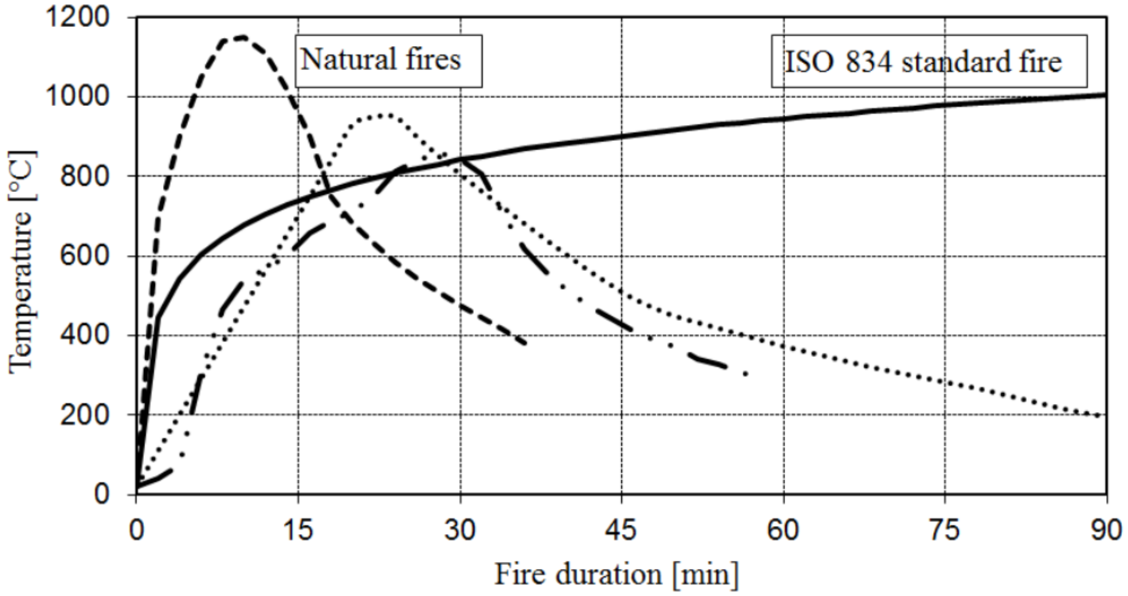


Figure 8. Fire curve for some natural fires and the ISO 834 [42]

Previously only the mechanical integrity of the GLT structure under high temperatures has been discussed, but some other important factors that are integral for the fire design in Europe are the containment of the smoke and the high temperature in an enclosure, as preventing their spread is vital to improve the safety of a building and to diminish the economic damage produced by a fire.

These properties called, integrity and insulation, are usually good for singular members due to the natural properties of GLT, but can see challenges in structures where the Glulam is connected to other sections, as the charring can affect the gaps between connections preventing a successful containment of the fire [43].

Knowing the mechanical resistance as well as the insulation, and the integrity of an assembly after a certain amount of time under the standard curve is then possible to assign a value in the form of minutes on the resistance towards a fire, this time is often displayed in the legislation as a requirement for buildings of certain characteristics.

None the less there have been some discussion among researchers that instead of just meeting a particular fire resistance classification some buildings should also be designed to self-extinguish once the source of a main fire has reached the decay phase, there have been several methods proposed to do this, for example the partial encapsulation of the structural members with a non-combustible cladding, variations in the geometry of the exposed members and the compartment they are in, etc [44].

2.3 Joints and their application in Glulam

Most structural elements need to be attached to others to be functional, for example columns are attached to other floors or ceilings, to do this the members are jointed together by different techniques, like the use of fasteners, glue or other methods that can provide some bonding between different pieces.

The objective of this section is to cover some of the structural behavior of these glulam joints and its components, afterward their performance under high temperatures will be discussed.

2.3.1 Mechanical behavior of Joints

It has been mentioned in a previous section that one of the benefits of GLT is the use of beams and columns as structural members that can act in unison to provide a sturdy system. To make use of this ability the members must be joined in such a way that they are capable to transfer the forces among the load carrying members, this is achieved with the use of adhesives, fasteners, lapped joints , or other types of joints[11].

In order to have a successful use of joints, it is important to assure they provide the right rigidity and strength, since they serve as the “bridge” in between different members is possible to have some higher stress levels than in some other sections of a structure.

These high stresses are a large part why for GLT, metallic joints or “mechanic connections” are used, the most common connections are fastened using either self-tapping screws or annular ringed shank nails, and if the expected load in a section are high these are supported by the use of plates and brackets[1][6].

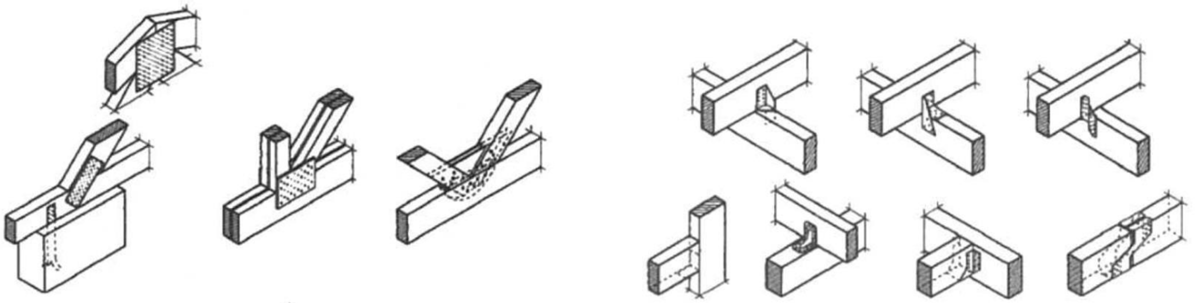


Figure 9.Examples of common connections using fasteners plates and angles [9]

Unlike regular screws, self-tapping screws usually have a continuous threading across the body made out of a forged or rolled wire across the shank, this leads to better imbedding and by result a more efficient load transferring between the joint and the timber; to handle these higher loads their threads are hardened which improves their resistance towards bending. The harder threads as well as the lower size of shank compared to the diameter of the threads allow the use of these screws in timber without the need for predrilling, this has been one of the mayor factors of their adoption since it means faster assembling[45].

On the other hand annular ringed shank nails work using a similar principle, this type of nail has the particularity of having rings across the main body that much like for the self-tapping screws increase the embedding force of the fastener in the timber element [46].

Self-tapping screws and nails are sometimes used to create timber to timber connections in the shape of splines and half lapped joints, these features however involve further work on the member of the structure and need significant care in order to assure a proper implementation, a solution that produces a good compromise in strength and ease of application is the combination of screws and metallic profiles used for transferring loads [7].

With the use of metallic plates or angles several benefits are gained, first the metallic piece acts as a source of load transfer across the fasteners, ensuring a more even distribution, they themselves act as another structural member providing strength to the joint, and finally the plates can impede the over embedment of the screws in the timber element [7].

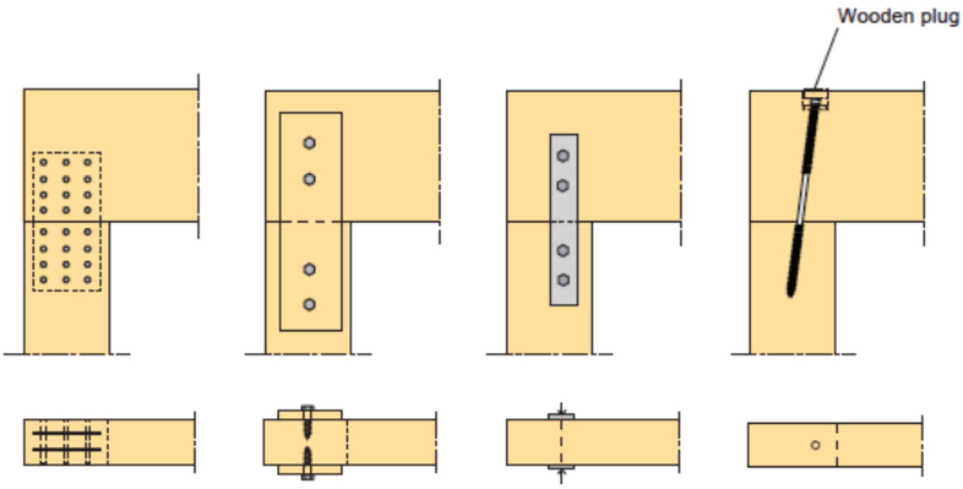


Figure 10.Examples of some common connections for glulam[1]

Once embedded the fasteners anchor themselves into the timber and can provide the timber structure some resistance both in shear an tensile loads, how much they can provide will depend of the embedment force, the properties of the area they are imbedded and finally the mechanical properties of the connector.

A way to calculate how the joints will behave in front of a load and whether they will fail is thought the use of the European yield model portrayed in the Eurocode 5 [23], EYM is based on the Johansen method which involves the resistance of the fastener and the crushing resistance of the timber.

This theory states that the strength of a joint will be defined once an effort is able to disrupt a connection, it also separates the possible ways of failure of a connection into 3 different causes.

More specifically the lateral strength of the timber connection could be given when the timber attached to the fastener fails limiting the embedding strength (failure mode 1); or when the system fails with or due to the formation of plastic hinges in the fastener (failure mode 2 and 3) [47].

A representation of these failure modes can be seen in the figure below, in number 1 is possible to notice a sketch of the crushed timber produced by the forces exerted on the connection, in the second failure mode the timber is also crushed but there is some deformation in the fastener, the last failure mode is mainly controlled by the plastic deformation in the metallic section.

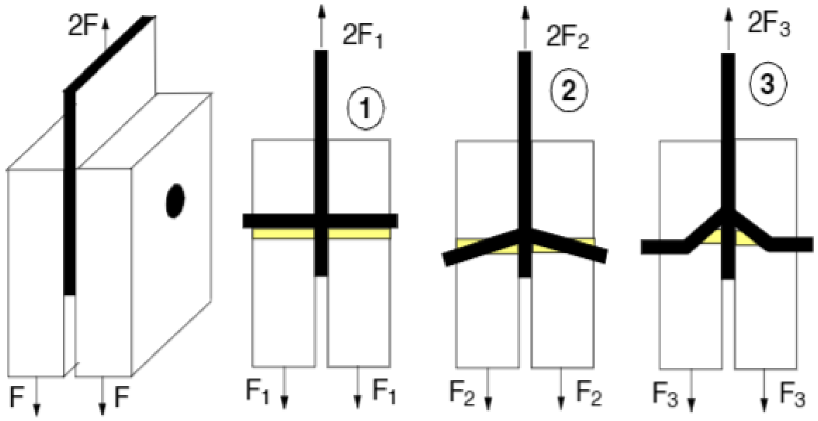


Figure 11.Possible failure modes for steel to timber connections [48]

Although the EYM is widely accepted and commonly used its utilization involves solving several equations involving a large number of variables, this makes the model somewhat time consuming, for this reason there have been some studies trying to find simpler methods to derive information on the behavior of timber connections[49].

An example of this is the research done by Uibel and Blaß[50] that has covered the strength of embedding and the withdraw strength for dowel type fasteners as well as self-tapping screws for CLT panels. In this research they tested several fastener with different properties according to the EN 383 and were able to show a relation between the diameter and type of the dowel with the force of embedment, for the self-tapping screws they additionally tested the withdrawal strength using a perpendicular force to the plane of embedment, the results produced by these showed a relation between the withdrawal and the diameter, penetration length , angle between the screw and the grain of the timber, and density of the CLT; these relationships can be seen below.

$$f_{h,pred} = 20\ d^{0.5}$$

Where:

$f_{h,pred}$: embedment strength for screws or nails in N/mm2

d: the diameter of the screw or nail in mm

$$R_{ax,s,pred} = \frac{0.44 .* \ d^{0.8} * l_{ef}^{0.9} * \rho^{0.75}}{1.25 * cos^2\varepsilon - sin^2\varepsilon}$$

Where:

$R_{ax,s,pred}$: force necessary for withdrawal for self-tapping screws in N

d: diameter of the screw in mm

l_{ef}: effective length of the screw in mm

ρ: density of the CLT in kg/m^3

ε: angle between the screw axis and the grain direction

In the previous section it was discussed that GLT can fail due to the effects of shear, this is not different for joints, it is possible and rather common to observe brittle failure in interface between the fasteners and the timber, this happens when the forces applied in the interface between the connection and the timber exceed the resistance in shear, creating a brittle failure characterized by a “block pattern” that is illustrated in the figure below, the likelihood for this event to be the main source of failure in a joint will depend in various factors such as the depth of the fasteners, their size, the dimensions of the glulam member and its layers.

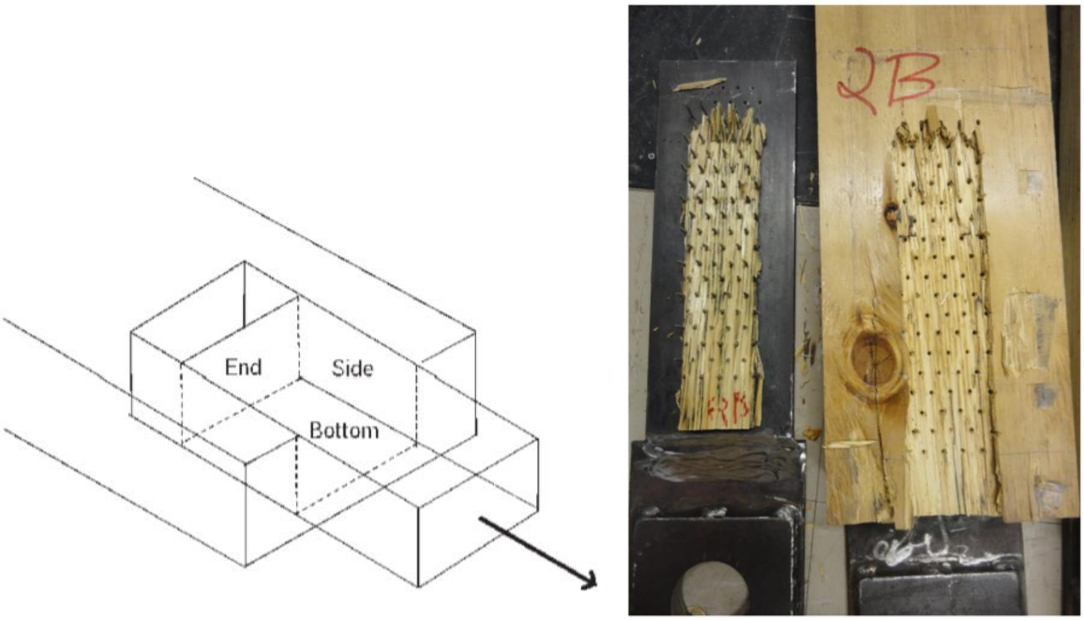


Figure 12.Sketch of a block failure for a timber member (left) [51] *and Failure in joint due to brittle/mixed behaviour (right)*[37]

This type of failure does not only occur in GLT it can also be seen in other types of timber members with high loads, the main difference is that the laminar nature of the product can cause the break of the assembly through the different layers of planks[52].

2.3.2 Fire behavior of joints

In section 2.2.3 the behavior of glued laminated timber under fire conditions was examined, but since a system will fail in its weakest link is worth to study the behavior of joints under these circumstances. Since timber joints have several different configurations it is expected to see a different performance depending on their characteristics.

The interactions between mechanical connections and timber under fire conditions are rather complex due to the high variability of fastening solutions added to the high variability in timber products, when a joint is heated, the external surface of the material gets heated, in the case of the exposed timber the heat will first evaporate the excess humidity in the material and will slower the temperature rise until the charring prosses starts.

For the exposed metallic part, the heat quickly rises, in the case of fasteners the temperature will be relatively high close to the exposed section but will have a lower temperature in the more embedded sections.

Even though the metallic fasteners are highly conductive the fact that they are surrounded by material allows for the dissipation of heat, this dissipation is first aided by the evaporation of the water inside the timber surrounding them, after this water is evaporated the heat transfer from the fire through the nail or screw can cause charring, warping and cracks thought the timber reducing the mechanical attachment to the substrate [53].

How this charring occurs will depend on the type of fasteners used, for example a smaller fastener will have a smaller area to dissipate heat which could cause a larger charred zone around it during the beginning of the fire exposure (this is illustrated in the next figure) [54].

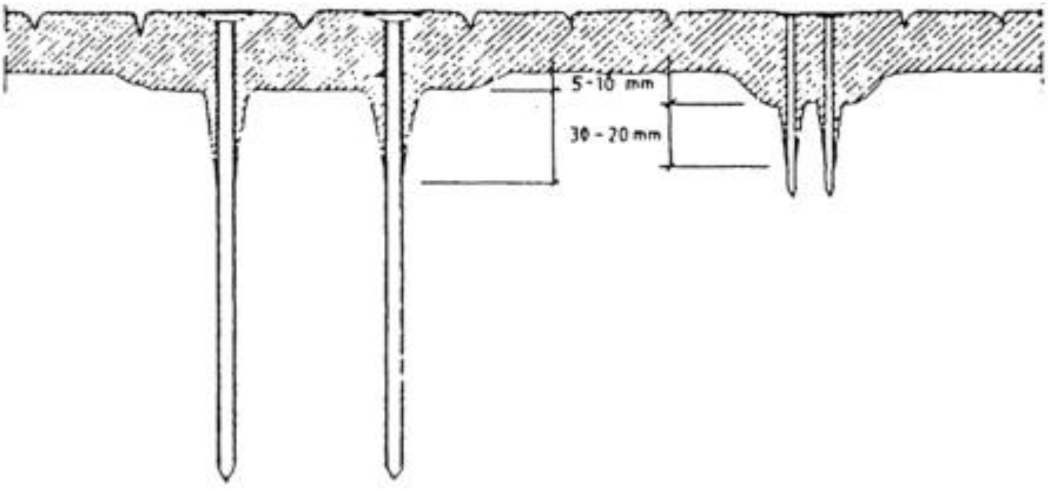


Figure 13.Diagram on the charring behavior of nails under fire conditions [54]

The strength of the joint is highly related to its temperature at any given time, partly because of the loss of the embedment due to the damage produced by high temperatures onto the timber and partly due to the reductions of the mechanical properties on the metallic pieces themselves.

The most common connections made from steel see a sharp decline in their mechanical attributes the higher the temperature is, in the case of plates or angles which are exposed to the fire this mean a reduction in the amount of shear that they can handle without failure, for this reason the load ratio during fire exposure is one of the most important factors defining the fire resistance of an assembly, because if the load at any point during the fire surpasses the diminished properties of the assembly the system will fail[55].

The picture below shows the embedment strength of various fasteners under different temperatures, even at moderately low temperatures it is possible to see a sharp decline on the mechanical properties produced by the loss of strength in the surrounding timber and the fasteners themselves. It is worth noting that the data used for the graph involved very long times of exposure to attempt to reach a steady state of temperature within the fasteners. In a real fire however it is likely that there will be some temperature differences due to the heat transfer between the fasteners and the substrate.

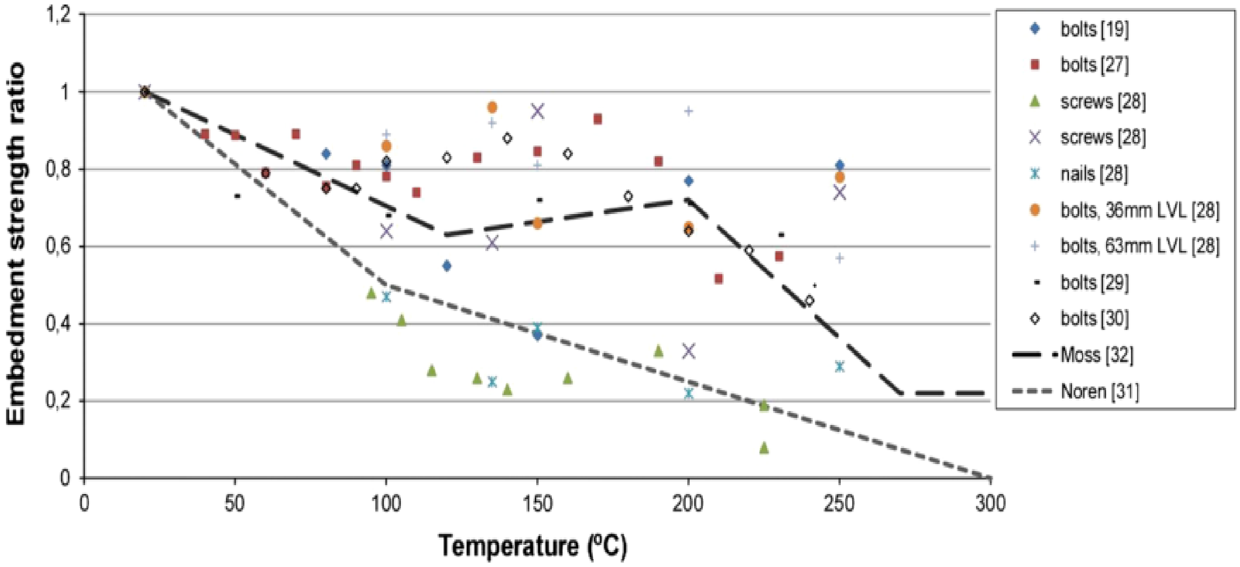


Figure 14.Embedment strength of various fasteners under different temperatures [55]

As the metal sections in the joints heat up the atoms that form these pieces get farther away between each other, weakening the bonds among them and by result decreasing their yield strength and elastic modulus[56]. This effect becomes more severe the higher the temperature is and can make the fasteners lose most of their mechanical attributes by 600 °C, this can be observed in the next stress-strain curve, we see that as the material heats the performance decreases significatively.

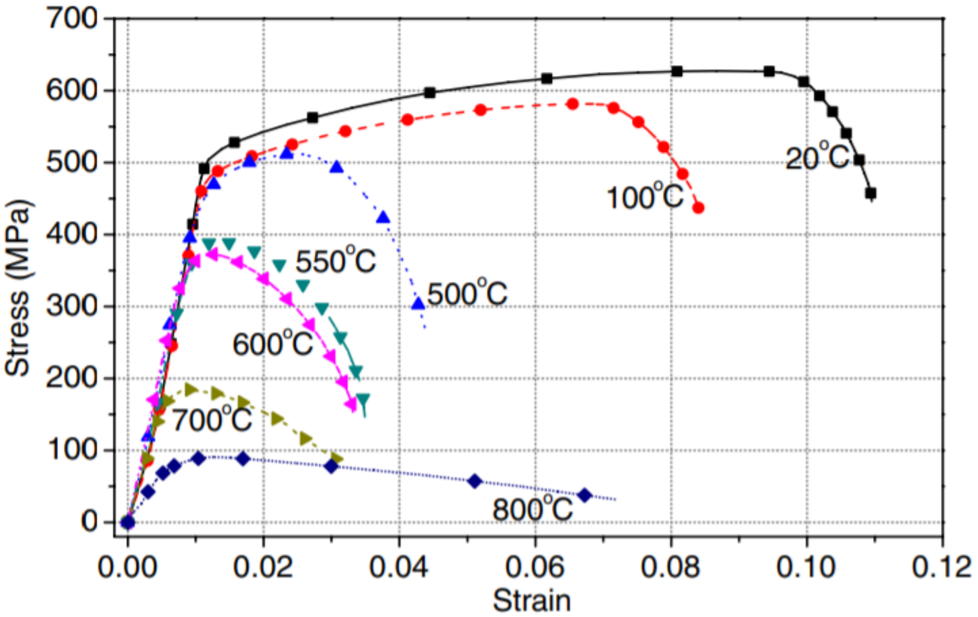


Figure 15.Stress–strain curve of a steel alloy at different temperatures[57]

How the mechanic fasteners change their properties at different temperatures will depend on the alloys used to make them. For example the presence of molybdenum niobium or chromium can help with the mechanical behavior under high temperatures [57],but the inclusion of alloys can result in a higher cost which has made the use of protected low alloy steels more common than their more resistant counterparts [58] .

The fire design of joints for timber product often follows the steps given by the Eurocode 5 [59], these rules follow connections with different fasteners under an standard fire curve, and offer two possible solutions to calculate the fire resistance, the use of simplified rules or the reduced load method.

The simplified rules assumes a defined time of fire resistance of 15 minutes for screws, nails and bolts without fire protection and provides some provisions to extend the time to 30 minutes if certain geometric requirements in the member where they are installed are met. On the other hand, the reduced load method calculates the shear strength on the fastener at a given time by using a constant attributed to the specific connector used.

From the simplified method we can see that the fire resistance that are permissible by the Eurocodes for unprotected joints are smaller than the requirement of high rise structures (more than 60 min [54]), for this reason they are often protected by passive means like gypsum boards.

Gypsum protection offers several benefits that can increase the fire resistance of timber joints, the main driver of this protection is the evaporation of the water contained within the material in a free state (around 3% of the weight of the gypsum) and in its crystalline form (around 21% of the weight of the gypsum), since evaporation is highly endothermic it uses some of the energy that would instead heat up the undelaying material[60]. Even after the total evaporation of the water contained within the gypsum the board can till delay the effect of a direct fire exposure[39]. This translates to a higher fire resistance on the joints [61].

If the application of gypsum protection is not possible or desirable, spaces inside the timber can be carved to insert the fasteners, plates or angles and in this way protect the joint without the addition of new material, this however can result in a higher cost since the glulam members need to go thought careful planning and machining in order to guarantee high tolerances and a proper design, which in turn can drive the prices of this kind of installation up[1].

Another method that is taken in order to protect exposed joints is the use of intumescent paint on their exterior, this paint, when exposed to a high temperature swells and chars giving the connection some additional protection, in the case of laminated veneer the use of intumescent paint on steel-wood-steel joints increased their fire resistance by 91% to 112%[62], this increase is very significant and could mean a higher fire rating for a certain assembly.

3 Experimental methodology

To expand on the knowledge previously portrayed, this section will describe the series of procedures taken to examine the performance of 4 glulam jointed systems, and will cover the assembly of the specimens studied, the tools used and the general steps taken.

3.1 Glulam Joints configurations

In order to test the influence of certain factors 4 different specimens were assembled with the objective of discerning the effect of some these on the fire behavior of GLT joints. These factors were, the size of the plate attaching the structural member (smaller vs bigger), type of mechanical fastener used (shank nail vs self-tapping screw), and protection of the joint (protected vs un-protected).

The base material used to create the joints were RAW glulam beams, these beams consisted of 6 layers of finger jointed spruce slates, with a thickness of approximately 33 mm per slate and an overall dimension of 200 mm of width by 90 mm of thickness and 4 meters of length. According to the manufacturer these beams are glued using a MUF adhesive, classified as GL28cs, have a humidity of 12±2%(pre-shipping) and a density of 460 kg/m^3[63].

These Glulam beams were acquired from a hardware distributor and were chosen due to their high availability in the market, as well as for their compliance to the relevant Eurocode standard, the CE EN 14080:2013.

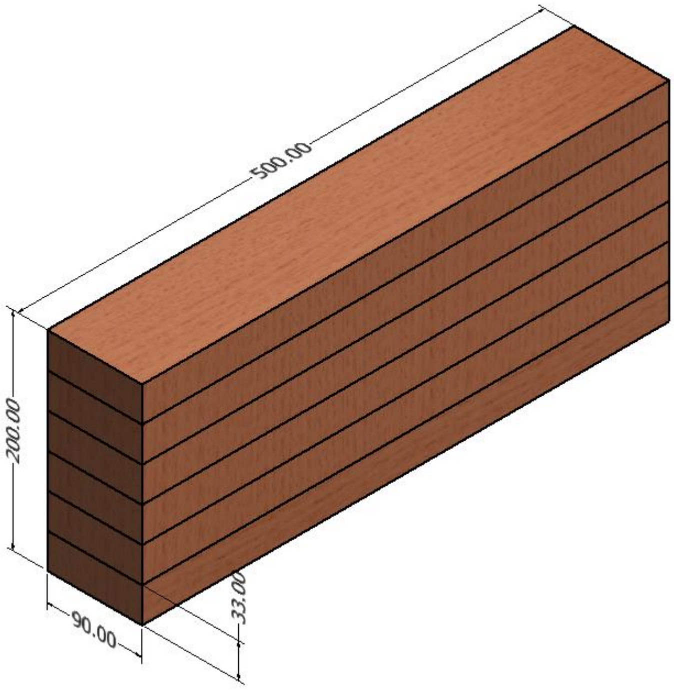
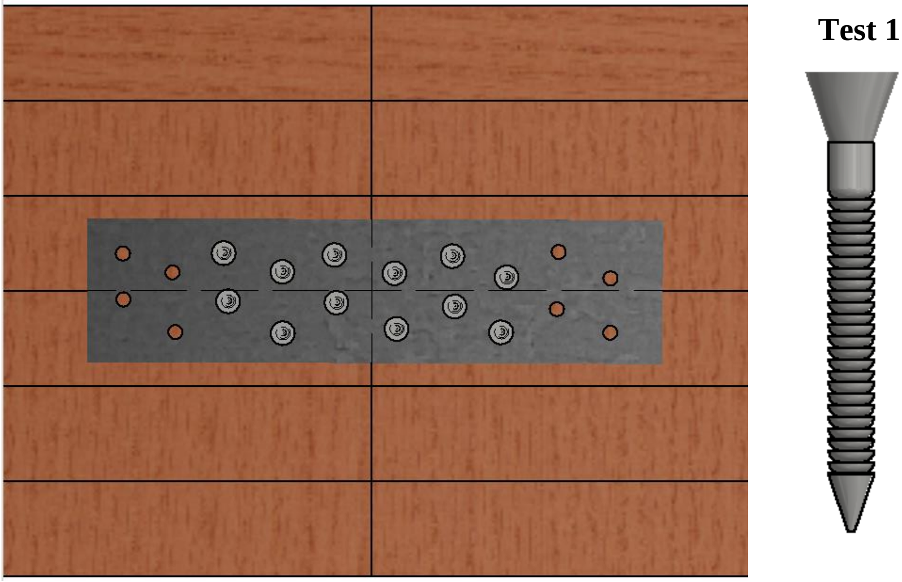


Figure 16.Glulam section with dimensions in mm

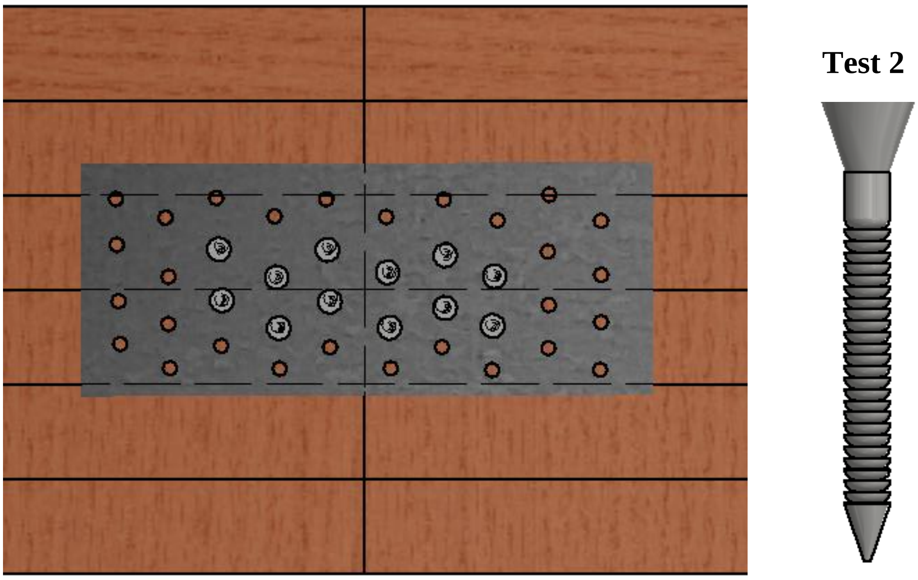
To create usable samples the beams were cut into pieces of 50 cm in length using a table saw, once divided these pieces were paired and separated into 4 different groups to test the various configurations, these groups were:

1. A 50 mm x 200 mm x 2 mm Plate joint using shank nails as a mechanical fastener
2. A 80 mm x 200 mm x 2 mm Plate joint using shank nails as a mechanical fastener
3. A 50 mm x 200 mm x 2 mm Plate joint using self-tapping screw as a mechanical fastener
4. A 50 mm x 200 mm x 2 mm Plate joint using shank nails as a mechanical fastener protected by a 12 mm gypsum board

All of these configurations can be seen in the figure below.



Test 1



Test 2

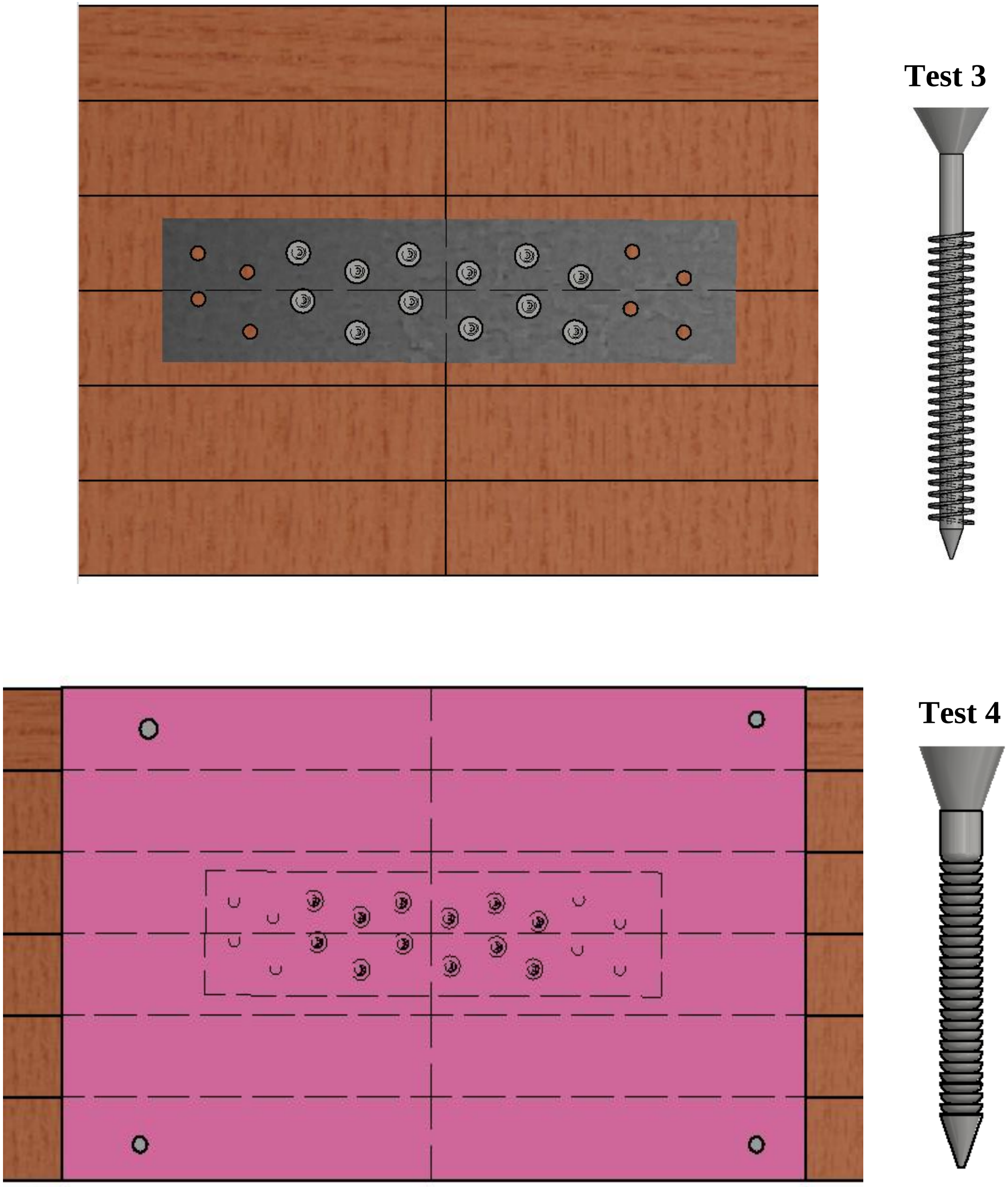


Figure 17.Joint sections for the four different configurations tested

All plates used were Simpson Strong-Tie branded and manufactured out of galvanized steel with a yield strength of 250N/mm^2 and an elongation before rupture of 19%, for the 50 by 200 mm plates only 12 out of the 20 holes were used to hold fasteners, the rest were left unused, to register the effect of using a bigger plate the 80 mm by 200 mm plate was also assembled using 12 fasteners in the same geometrical configuration as the smaller plate.

For the group 1, 2 and 4 Simpson strong-tie shank nails were applied, these nails had a diameter of 4 mm and a length of 40 mm, as for the group 3 these nails where interchanged by Fermacell self-tapping screws with a diameter of 3.9 mm and a length of 40 mm .

For the assembly of the test specimens, 2 pieces of the previously cut glulam beams were held together into each other with mechanical clamps in order to reduce the size of the gaps between the parts, once enough pressure was applied to prevent any movement the plates were placed in the middle of the two pieces and fastened with either nails or screws.

For each specimen two plates were used, one on the top and one on the bottom, the purpose of the use of two plates was to diminish any bending produced by the inherent eccentricities of the system. To simulate the average conditions in a construction site, no predrilling was used for the embedding of the nails or the screws.

Once the plates were installed in the members one of the specimens was taken and was fitted with a 12 mm thick gypsum board of 200 by 240 mm covering the plate that would be exposed, while the unexposed side was left without protection , additionally the sides between the glulam and the gypsum board were filled with rockwool to insulate the section and more closely follow the behavior of a fully protected timber member.

3.2 Load application

Once the joints in the 4 specimens were assembled, a load was applied in each separate test to emulate the forces that a structural glulam member would be subjected during its use. Due to the limitation on the size of the mobile oven available for the testing it was not possible to proceed with the use of conventional tensile machines to produce these loads, so in order to create the tensile forces needed for the test a new setup was designed.

The first step taken for creating this setup was to attach a 8 mm thick steel L profile to each of the ends in the tested samples, this fix was done using 5 Expandet screws of 7.5 mm in diameter and 92 mm in length, the purpose of these screws was to carry any lateral load produced onto the profiles to the wood creating a load in the joints as previously discussed.

The lateral force was produced with the use of a 5 ton hydraulic jack, which was attached to a hydraulic pump fitted with a pressure gauge, this system allowed to generate pressure in the jack from a distance and to keep a constant level of pressure within the system. This jack was mounted in the beam between the L profiles, but before this a fine layer of rockwool was applied at the top of the specimens to protect the jack from the heat and prevent the heating of the hydraulic oil as this would mean an increase on the pressure of the system.

To further prevent the heating of the hydraulic system a timber bar was used to carry the loads from the attached jack to the other end of the sample, this allowed the jack to be separated from the fire exposed area.

Additionally the system was also fitted with a steel brace on top of the timber bar, this steel brace had the purpose of preventing any vertical movement from the jack or the bar produced by the eccentricity of the forces; to reduce friction a metal plate with a rolling pin was installed on the timber bar.

Once the jack was placed and secured a pressure of 80 bar with an equivalent load of 4.2 KN was applied using the manual pump.

Figure 18.Experimental setup and jack system

3.3 Study of the forces present in the samples

To understand the behavior of the mechanical system established and the repercussions of the loads in the fire testing a brief analytical study on the forces and possible failure mode was performed. The first step taken to see the behavior of the applied forces was to create a computerized model of a glulam member with the loads produced by the jack system.

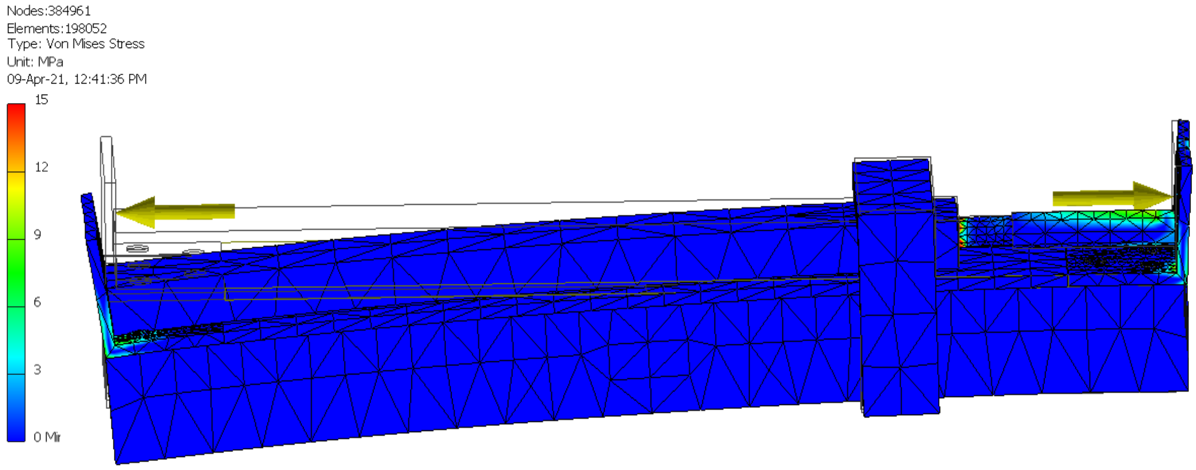


Figure 19.Stress analysis of the samples and their loading system made using Inventor

We can see that the jack in this case due to being off center produces a moment in the overall sample that generates a series of tensile forces on the upper part of the sample and some compressive forces on the bottom, this shows as a small bending angle in the jack, the top timber board used to carry the load, as well as for the exposed glulam .

It was mentioned before that the tensile force applied to the members was of 4.2 KN, the simplification was made that the load were distributed homogenously through the material but as we saw in Figure 19 these produced an overall moment and some bending given by the force and the distance from the jack to the center of the GLT, this moment will be countered by the moment induced by the weight of the setup, in our case around 19 kg. This generated the overall moments displayed below.

$$M_{jack} = 4.2\,KN * 0.07m = 294N * m$$

$$M_{weight} = 19kg * -9.81\frac{m}{s^2} * \frac{1\,m}{4} = -46.6N * m$$

$$M_{total} = -247N * m$$

The moment generated by this will produce an additional tensile stress in the top and a compressive one in the bottom of the members given by

$$\sigma_{tension-compression} = \pm\frac{M\,y}{I} = \frac{-247N * m * 0.045m}{\frac{1}{12} * 0.2m * (0.07m)^3} = \pm 1.9\,Mpa$$

These stresses will be carried through the joints as well as the tensile forces of the system, as the plates used act as the transporting medium of these forces it would be advantageous to examine the loads produced in them, for the smaller plates we have that the tension produced due by the transversal load will be

$$\sigma_{tension\ in\ small\ plates} = \frac{2.1\,KN}{2mm * 40\,mm} = 26.52\,Mpa$$

Considering that the yield strength of the steel plates is 250 MPa (as reported by the supplier) we have that the load produced in tension in both plates will be around 10.4% of the load before failure in tension, none the less this approximation is not entirely true as does not take into consideration the compressive or tensile forces produced by the bending, it also assumes that the loads carried by the bolts connecting the L profiles will carry loads uniformly across the glulam member which is most likely not accurate.

Another possible way of failure for the system is through the loosening of the fastener if the lateral force exerted on the nail is superior to the withdrawn strength, in the case of glulam just like mentioned in the theoretical section of this work this force usually comes through the use of the European yield model, however to simplify the calculation on these forces the formula for the embedment strength defined by Uibel and Blaß [50] will be used, in the case of the nails we have the following withdrawn force per fastener:

$$R_{ax,s,pred} = \frac{0.44 .* \ 4^{0.8} * 35^{0.9} * 460^{0.75}}{1.25 * cos^2 90 - sin^2 90} = 3249\,N$$

Considering that each test possessed 12 nails or screws in each side, the force needed for failure due to the extraction of all the nails ,77.9 KN, surpasses the one needed for the failure in tension due to the yielding of the plates which had a value of 40 KN (this value is extracted out of effective area of the smaller plates and its yielding strength).

Another possible source of failure is due to the forces in tension within the timber but since average values for glulam in tensile strength are around 24 MPa [64] this will be highly unlikely as the previous two system (the nail or the plates) will fail much quicker.

This means the most likely source of failure will be the exposed plates, however this is only taking into consideration the tensile forces and viewing this setup as a purely tensile system, this is not entirely true as several factor such as the moment caused by the eccentricity in the load application, the directly opposed moment produced by the weight of the setup, the positioning of the screws in the L profiles, the angle of these screws, difference in the angles between the connected GLT pieces, and many other factors will alter the way each load was transferred during the testing.

For this reason, is necessary to mention that this testing tried to replicate the complex integration between the tension, compression and bending forces that occur in joint assemblies during their field use rather than just one force.

An example of this complex integration of forces is the one seen in pre-stressed glulam, these type of members are used to increase the load bearing capabilities of the timber members [65] and follow much like the described system a series of tensile and compression loads.

It must be mentioned that the loads used account for roughly 10% of the maximum theoretical force for failure, in the real-world structural members are expected to be subjected to much higher loads. Even so the effects of charring and overall mechanical behavior during the fire are expected to follow a similar patterns to a more loaded member, with some differences on the type and time of failure (a higher load could cause plastic deformation as well as a faster failure).

To see the behavior of the previously mentioned assembly the use of the jack system was deemed suitable as it was able to produce tensile loads as well as moments that somewhat resemble the forces that occur in a normal building. The samples were tested according to the steps described in the next section.

3.4 Execution of the fire test

To test the glulam joint under fire conditions the loaded members were exposed to an ISO 834 fire curve using a mobile oven provided by the danish institute of fire and security technology.

This oven consisted of a mobile housing that contains several electrical heating elements that can heat the enclosure within the oven to follow the fire curve, to follow this curve the oven possesses 3 attached thermocouples (in different sides of the oven) that can measure the temperature at any given time, these measurements are averaged between the three of them and compared with the curve by a computerized system, if the temperature is insufficient more power is supplied to the heating elements and if the heat exceeds what is expected from the curve at a given time it will turn the elements off until the temperature normalizes to the one presented in the curve.

Along the 3 internal thermocouples the oven has an auxiliary system that allows attaching several other thermocouples and record any temperature differences measured by them, these measurements are recorded along with the time as to grant the ability to measure the temperature on a sample if needed be. In the case of the experiments thermocouples were attached to the samples under the plates (Figure 20) and held with staples, to measure the temperatures in the steel-timber interface. More specifically in these 4 tests, group 1 and 4 had thermocouples installed both in the upper plate and the exposed plate (one in each side), for test 2 and 3 only the exposed plate was fitted with a thermocouple.

On top of the oven there is an aperture of 50 by 50 cm that allow to position the samples and supply the exposed area to a desired heating curve, the perimeter of this top is covered by insulating brick that diminishes the heat transfer to the areas of the samples that are not exposed, for these test as the samples were insufficiently big to cover all of the area of exposure the use of a layer of rock wool was needed to cover the rest of the top of the furnace as to prevent lateral burn off in the samples.

The fact that the top was covered with rockwool meant that the test did not have a significant pressure build up during the test, as the hot gases could escape through the gaps of the set up with relative ease. This was confirmed with pressure measurements taking during the tests, indicating no more than 6 pascals of difference between the inside of the oven and the ambient pressure.

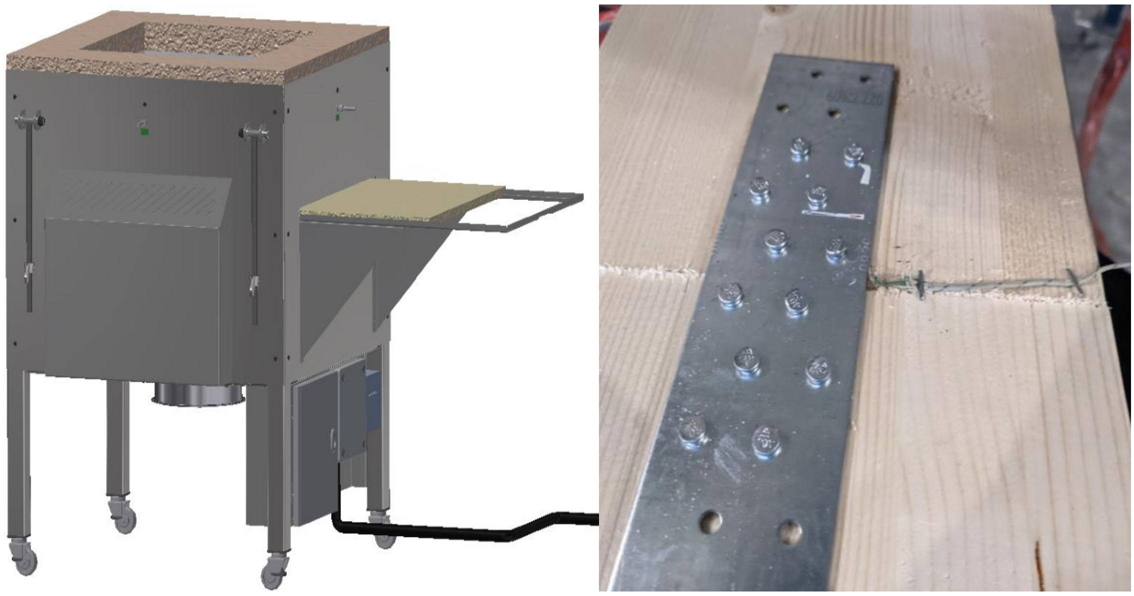


Figure 20.CAD sketch of the mobile oven used (left) provided by DBI, placement of the thermocouple for sample 1 (right)

To perform the ISO 834 curve the heating elements within the oven were preheated for 30 minutes before each test, as to prevent increasing the temperature of the oven before the testing started an insulated board was placed between the heating coils and the top of the furnace. Once the test samples were ready this board was taken out and the temperature of the oven was let to follow the desired temperature.

For each of the tests the samples were placed on top of the oven with one of the sides exposed, as was mentioned before any unused area on top was covered with rockwool. After the samples were placed in the oven the pressure of the jack was raised one minute from the start of the test using the pump, for each of the test the pressure was raised to 80 Bar, which means a value of around 4.2 KN in a lateral force (the calculation of this value can be seen in the annex of this dissertation). The pressure within the jack was kept constant by pumping every time there was some noticeable losses observed in the pressure gauge of the pump.

Once each test started the gap between the glulam pieces in the joint were measured to see any possible displacement produced. In the first test, a ruler was placed on top of the test sample but the smoke created during the test did not allow for an accurate reading of this gap from a distance, so instead in the rest of the tests a measurement of the distance was recorded every 7 minutes by positioning a ruler directly in the upper gap of the samples and recording the dimensions of the gap.

Figure 21.Specimen 1 exposed to the fire curve

All samples were exposed to 30 minutes of the fire curve as to compare the results with the maximum allowed time proposed for unprotected joints in the Eurocodes, once these 30 minutes passed the pressure on the jack was released and once the pressure gauge marked 0 on its dial the jack was removed from the sample, after this the sample was lifted from the oven and placed on the ground.

Since the glulam members are composed out of combustible material this meant that even after their extraction from the oven, flames could still be seen on the exposed area, as to prevent further charring a water hose was used to extinguish any visible flames, the pressure on the hose was kept at a minimum as to prevent any water damage that could harm any results produced by the fire test.

Figure 22.Removal of test sample 1 from the oven (top), extinguishment of sample 2(bottom)

4 Results

This section has the intention of displaying all the recorded results from the tests performed according to what was mentioned in the previous chapter, as to facilitate the understanding of the results, this segment will be divided in different sub sections depending on the nature of the results. Subsequently the different samples will be compared to each other as to observe the effects of each of the variables on the behavior of the joints under a fire scenario.

4.1 Temperature measurements

The first aspect during the testing that was measured was the temperature of the oven as well as the temperature in the tested plates, like is stated in the experimental chapter only the test 1 and 4 had both sides with thermocouples, the rest, test 2 and 3, only had the exposed side examined.

The result of these measurements were compiled using graphs showing the recorded temperature vs the time of the testing, additionally the temperature produced by the ISO 834 curve was also added to these graphs to see how the temperature in the oven compared to it.

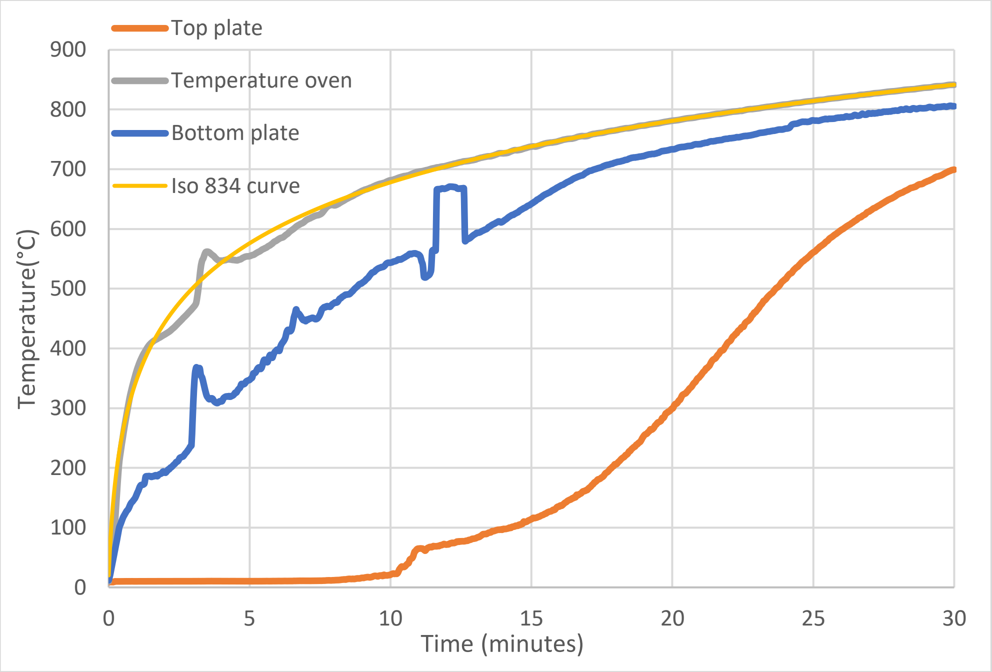


Figure 23.Temperatures recorded during test 1

In Figure 23 we can see that the temperature generated by the mobile furnace adapted quite closely to the one stated in ISO 834, the only mayor difference occurred at around 3 minutes where the temperature in the oven spiked and surpassed the control curve for a matter of seconds, this spike then normalized and continued until the 30 minutes of testing passed.

As for the temperature on the bottom plate we see an immediate temperature increase as soon as the test starts, the rate of this increase slowed down at around 200 degrees signing the evaporation of water within the wood and the start of the pyrolysis process, after a few seconds this leads up to the ignition of the sample generating a sudden spike in the temperature recorded by the thermocouple, this temperature then lowers to around 300 degrees; this phenomena goes in line with what is expected according to literature, since researchers such as Babrauskas[66] reported the ignition of timber products within this range.

The temperature continues to increase steadily after this until minute 10 when again there is a slight reduction followed by a momentaneous increase of temperature of about 130 degree Celsius.

For the temperature in the top the rate of growth remained small during the first 10 minutes then it saw an increment of about 60 degrees in about a minute, if the bottom plate temperature is compared to the one on the top at this time we can see that the rise of the temperature in the upmost thermocouple happens when the temperature at the bottom decreases, this could signal an intrusion of fresh air into the system through the gap making the temperature briefly decrease and the rate of combustion increase in the oven. This also comes attached with the outflow of hot gases that would in turn heat the upper plate.

By the end of this test the temperature perceived by the top thermocouple only differed by 100 degrees Celsius from the one on the bottom showing a clear intrusion of the hot gases of the oven trough the jointed element.

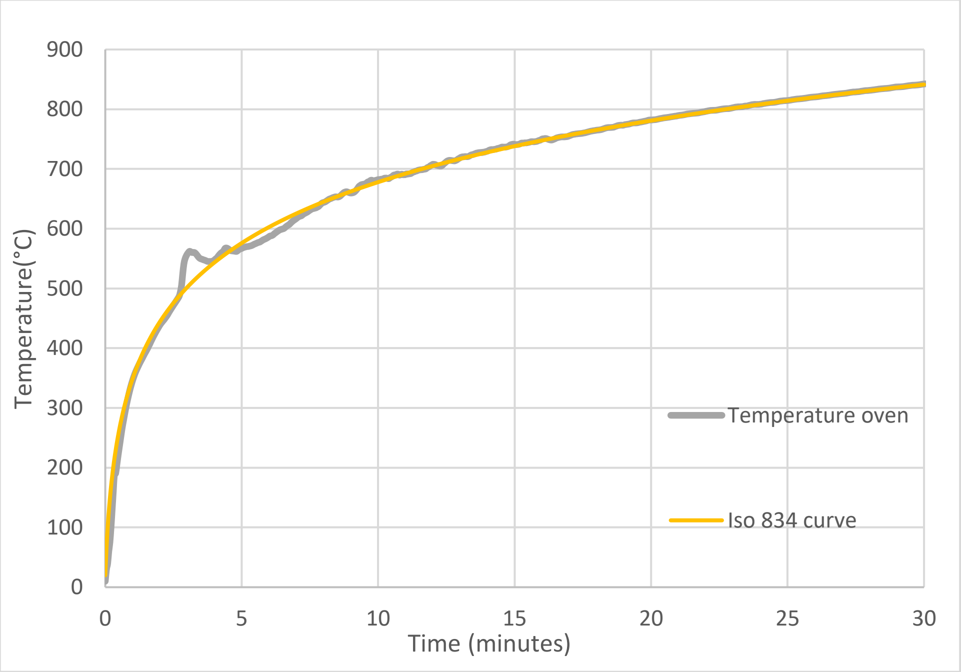


Figure 24.Temperatures recorded during test 2

During the second test the lower thermocouple fell off during the installation of the testing setup onto the oven, this made it impossible to measure the temperature on the bottom joint. However the temperature of the oven was still recorded and it shows a similar pattern as the one for test 1, with a spike of temperature produced at 3 minutes, that could be caused by the start of the pyrolysis within the sample.

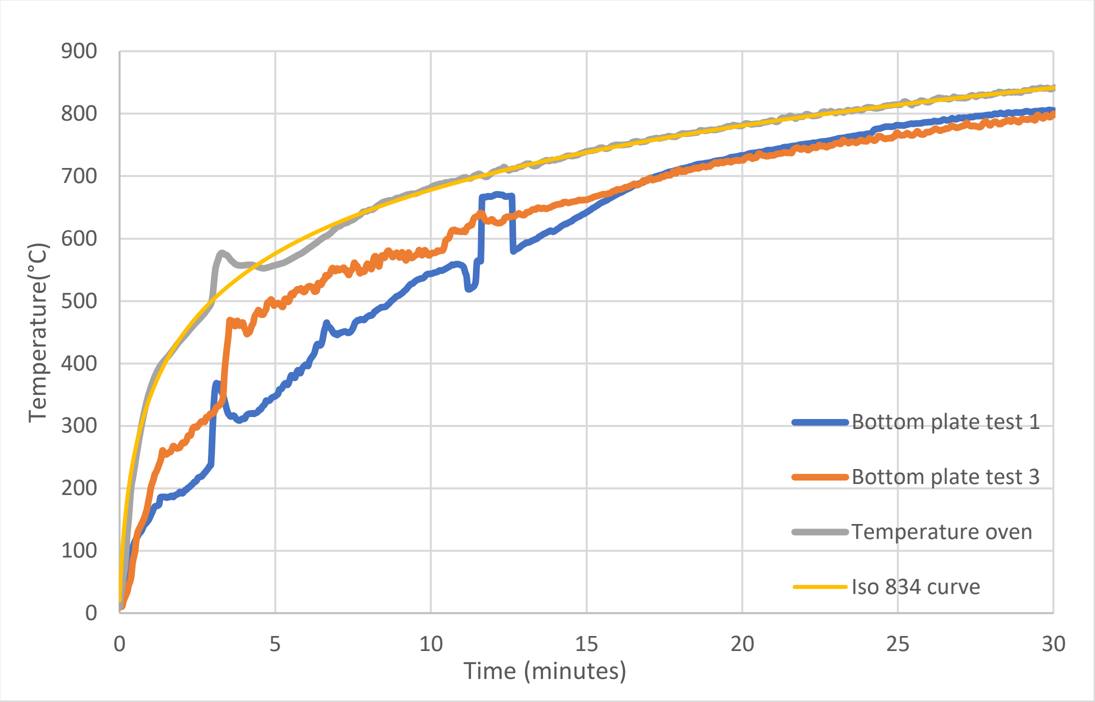


Figure 25.Temperatures recorded during test 3 compared to the bottom temperature of test 1

For the third test we can see again that the temperature in the oven followed quite closely the temperature of the furnace except for the slight increase of temperature at minute 3. To compare the result obtained during the test 1 the results of the bottom joint were also included as to annotate the similarities among the two experiments.

In the 3rd test we see a faster growth in temperature and although the pyrolysis starts at similar times this one leads to overall higher temperatures and unlike for the first test this rise did not disappeared after a few seconds but rather increased constantly until the test finished. Is also worth mentioning that for test 1 and 3 the temperature curves met after 16 minutes and shared a similar behavior during the rest of the test.

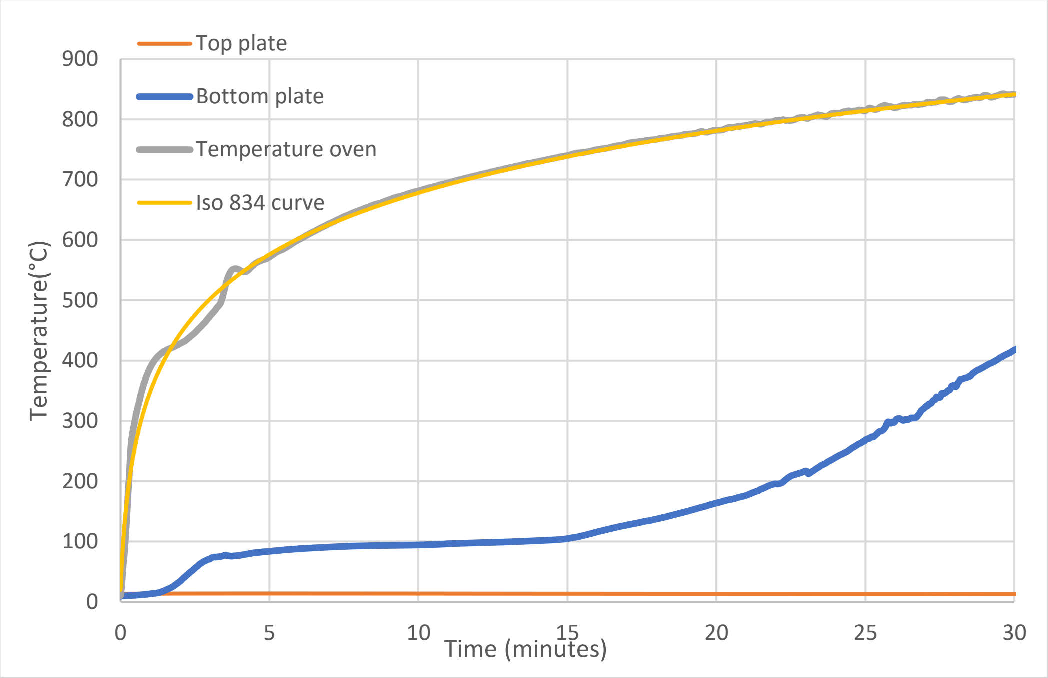


Figure 26.Temperatures recorded during test 4

The results in the protected member seen in Figure 26 had a different behavior than the one observed for the past tests, at 3 minutes we start seeing the effect of the pyrolysis on the oven temperature but this time is smaller since most of the timber used during the test was covered by gypsum.

As for the temperature of the bottom plate we see that it holds a temperature of around a 100 degrees Celsius for the first 15 minutes if the tests, indicating that during this time the gypsum was releasing water from its structure and maintaining a somewhat steady temperature under the joint, after this however the protection of the gypsum diminishes and the temperature starts rising markedly, this increment however is still lower than for the unprotected members.

In the previous graph we can see that the temperature in the top plate remained the same during the whole test, additionally it was the only test without visible smoke propagation through the gap of the joint while the sample was being assessed.

4.2 Visual analysis of the samples

After recording and tabulating the data produced by the thermocouples during the fire tests, the samples went through a prosses of visual analysis, in this analysis all the differences that could be discerned were catalogued for each individual test.

Figure 27.Exposed side of the Test 1 and 2 after 30 minutes of the ISO 834 fire curve

In Figure 27 we can see that the exterior surface between sample 1 and 2 showed no major differences, the same case was also seen in the experiment number 3, it was possible to observe charring in the exposed area with some additional burning and discoloration in the zones contiguous to it.

Some crackling was seen on the exterior of each sample, and on the gap present at the joint a round-off phenomena was observed, meaning that the charring occurred both in the exposed face as well from the gap to the sides of the sample. This meant that the size gap in the exposed area was not constant trough the sample instead the gap size was recorded to be bigger closer to the exposed area.

After being extinguished the first 3 samples had their exposed plates removed manually without any kind of resistance, in the case of sample 1 and 2 some nails were observed to have fallen off during the moving of the sample, showing a rather low attachment to the substrate.

Figure 28.Exposed side of the protected sample after 30 minutes of the ISO 834 fire curve (test 4)

In the case of the sample protected by the gypsum board the unprotected areas showed a similar pattern observed in the test 1,2 and 3 but on the areas that were covered the presence of charring was smaller than in the previous tests , as for the gap, some rounding in the corners of the material like the ones observed in sample 1, 2, and 3 was reported, but in this case the effect of this "round off " dissipated approximately at 3 mm from the exposed to the unexposed side.

In the case of the protected joint, the mechanical fasteners as well as the plate showed no noticeable loss in strength, and underneath the plate the timber presented some discoloration but no charring, unlike the surrounding of the plate where charring did occur.

After disassembling the 4th joint, three different cuts were made through the glulam profiles each of approximately 2 centimeters of depth and going from the interface of the two pieces present in the joints to the end of these pieces, the pictures of these cuts can be seen below in Figure 29. It should be noted that this image is not up to scale as some images were resized to ease the comparison between the samples.

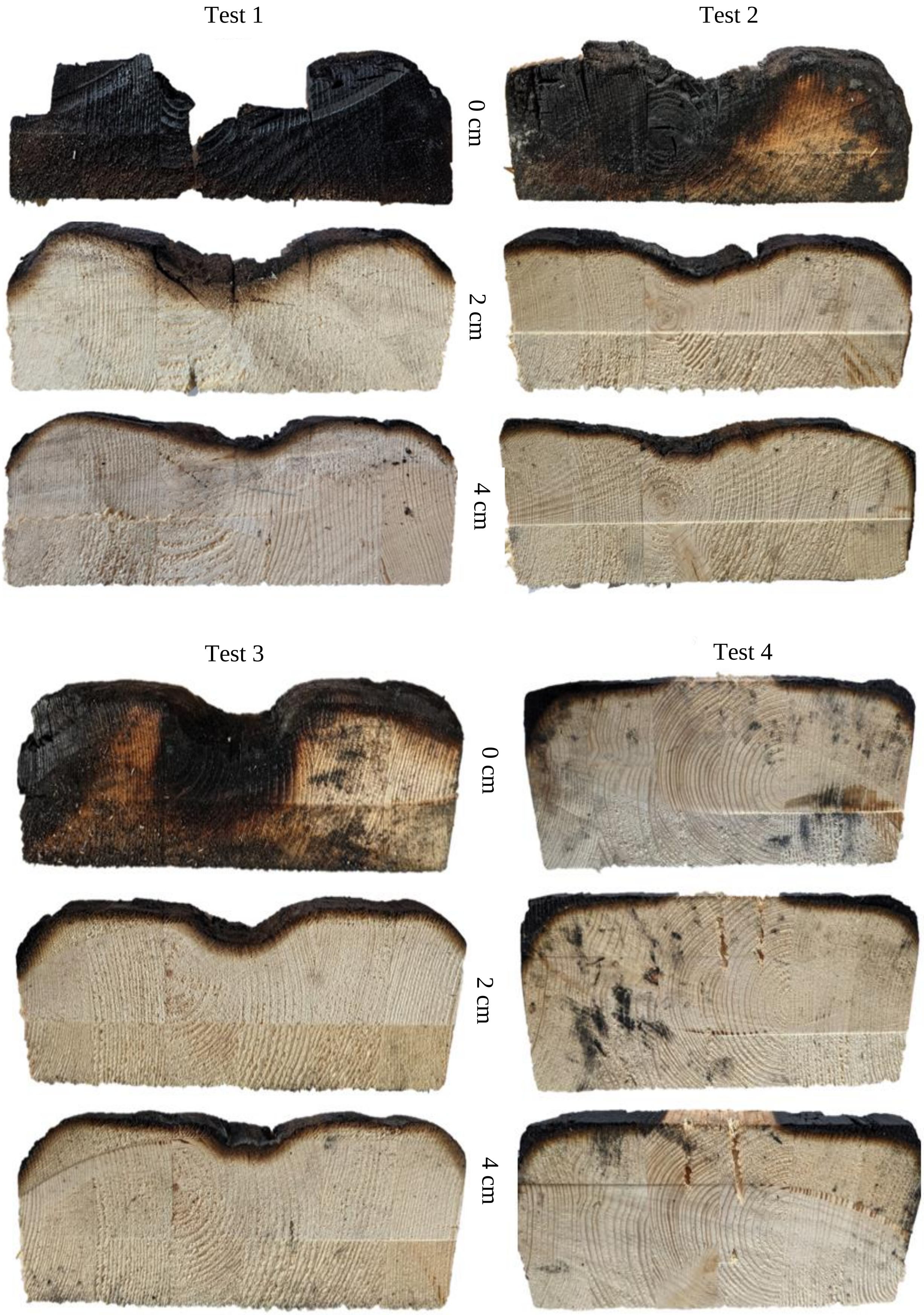


Figure 29.Cutouts of the tested samples, from top to bottom each image represents a 2 cm slice from the jointed area to the free side

In the last picture we can appreciate the different charring patterns produced by the diverse characteristics present in each sample, from top to bottom is possible to see that for all tests the charring decreased the farther away from the gap they were, as well that every sample had a "rounding-off" in the corners characteristic of 2 dimensional charring.

It is also clear to see that the initial cut of the first test, (nails and a small plate) saw the most damage in terms of charring, so much so, that the first cut produced broke during the sawing of it. This charred area extended to the whole slice and generated visible fissures in the locations where the glulam was bonded together, creating an incomplete delamination within the material.

This phenomena is clearer to see in the second cut, in here three different black cracks can be seen near the bonding interphase of the slates composing the glulam, these cracks were not significant enough to propagate through the whole glued laminated member and split it but they were significant enough as to increase the pyrolysis of the area surrounding them, this is denoted by a larger "halo" of darker timber when compared to the other samples. The delamination in the 3rd cut for the first sample was not as visible, occurring mostly closer to the gap.

Figure 30.Second cut of the first test showing signs of delamination

It is also worth noticing that for each successive cut the divot in the middle reduced its size, this divot became imperceptible after roughly 10 cm from the gap, which was the distance covered by the plate using during the test.

For the second test (a larger plate with nails) the first cut remained mostly intact during the cutting showing more structural integrity than the first test, in this cut also the severity of the fire condition seemed to be lesser, as spots of the original color of the timber still persisted even after the 30 minutes. Something harder to see in this cut is the small delamination occurring in the third board of timber (left to right), this is showed in the next picture.

Figure 31. First cut of the second test showing signs of delamination

Much like for the first test the second one saw a reduction of the internal groove as it distanced itself from the jointed interface, this indentation however did not had the same characteristics, in this case it was more wide but had less of a depth when compared to test number 1 or 3. Another interesting aspect is that the deepest points of the divot were observed in the 3rd board where the delamination occurred .

In the third test (nails and a smaller plate) also saw less burning in the adjacent area between the boards, much like for the second test the exterior was not completely charred out conserving some features of the original timber member. The groove in this case was even narrower than for test 1 and had a charred depth in between the test 1 and 2.

The most distinct result from all of these tests came from the one protected by the gypsum board this one saw only some minor charring around the corners and no charring underneath the plate, the differences between the different cuts was also not as significant as in the other tests showing an almost constant pattern of charring on the corners.

For the cuts at 2 and 4 cm the cuts were aimed at the locations where the screws previously were, this was done to see possible charring or discoloration in the area surrounding them, in this case charring was not visible in the timber-plate interface but in the internal surface within the hole some minor discoloration was observed.

4.3 Charring analysis

The calculation of the charring rate was done by measuring the size of the glulam members after the testing and extracting by differences the quantity of wood lost due to the test, there were 2 different sets of measurement done for each test, a group of measurement were done in the divot where the mechanical fasteners where imbedded, and the other set was done father away from the gap as to measure the charring without the influence of the joint (a picture of this can be seen in the annex).

For the depth in test 1,2 and 3 three measurements were taken from the deepest point of the divot for each of the slices seen in Figure 29 using a digital caliper. For the unjointed area one measurement was taken for each of the tests in the zone contiguous to the joint.

The average of these measurements is laid out in Table 1 as well as some other information that may complement the understanding of the influence of the studied factors on the charring behavior. This table only covers the three first test since the protected sample did not had visible charr under the fasteners.

The depth and the charring rate results come with a ± symbol that represents the standard deviation from the average measurements and calculations.

Table 1.Charring rate, depth, width of the charred are for test 1,2 and 3

	Depth of charred area (mm)	Width of charred area (mm)	Charring rate (mm/min)
Test 1	39±3	55	1.3±0.1
Test 2	35±2	64	1.16±0.07
Test 3	37±4	49	1.23±0.13
Unjointed area	23±2	200	0.76±0.07

With the charring rate is also possible to measure the effective depth of each individual fastener in respect to time as it will be the original depth minus any material below them that has charred off. Is common practice to calculate the depth using the tabulated charring rate for a material to estimate this amount and adding a 1.5 safety factor due to the increase in heat flux produced by the fasteners, but as the previous table shows there was a different charring rate for the zone where the joint was embedded and this one surpassed the safety factor mentioned by the Eurocode, for this reason the depth was calculated with the two distinct charring rates as to compare the real world resistance and the one portrait by the Eurocode.

Once having the effective length is possible to use the formular laid out by Uibel and Blaß [50] to calculate the withdrawn force needed to extract the fastener, this formula can be seen in chapter 3. The forces for test 1,2, and 3 were compiled in a graph as well as the force using the charring rate recommended by the Eurocodes, this graph can be seen below. As to be conservative the charring rate used to calculate the Eurocode method was the one registered from the unjointed area seen in Table 1, meaning a charring rate of 0.76 mm/min multiplied by a safety factor of 1.5.

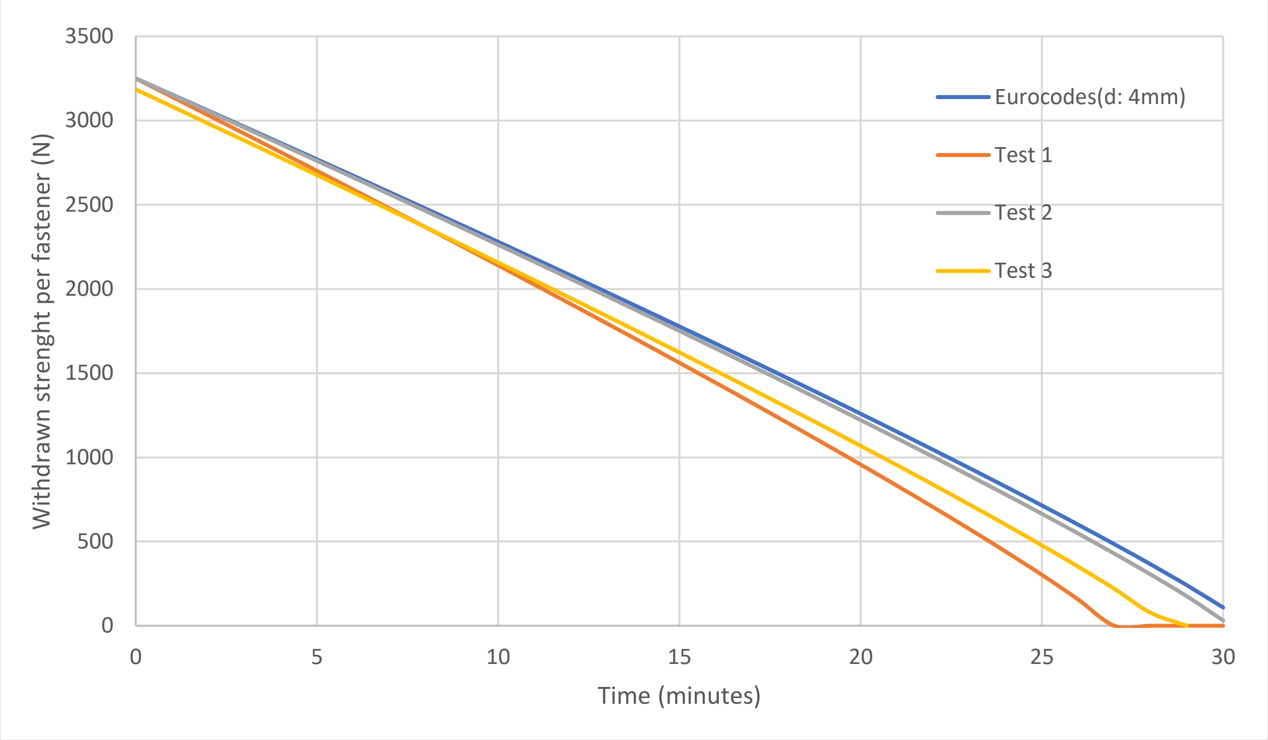


Figure 32.Withdrawn strength of the fasteners according to their effective depth and time

In Figure 32 we can see the withdraw strength needed to pull out the fasteners for test 1,2 and 3 as well as what is recommended by the Eurocodes, a clear result is that the force needed to pull the fasteners embedded in the jointed area was smaller than the one calculated using the Eurocodes; this difference between the results became more severe as the time of the testing passed, for example by 15 minutes the test 1 had 92.6% of the strength predicted by the Eurocodes and 45% by minute 25.

For the withdraw strength according to the Eurocode a diameter of 4.00 mm was used for the size of the fastener, the same thing was done for test 1 and 2, for the third test a diameter of 3.9 mm was used as this was the size of the screws used. This explain why for test 1, 2 and the Eurocode line have the same starting point in the graph showed in the previous figure.

The most severe difference between the values used by the norm and the values obtained in the joints was for the test 1 having none withdrawn force left 4 minutes before the one predicted by the Eurocodes. This result is followed by the performance of the sample using screws and finally for the test using a bigger plate.

As for the result using a bigger plate is worth mentioning that it follows quite closely the one provided by Eurocode, having only a difference of 30 second in the time to reach the total loss of embedment force.

Since all 3 tests showed an under-conservative value when compared to the one predicted using the Eurocodes, this means that a design that follows the minimum requirements without the use of additional safety factors could result in an unsafe assembly. None the less this graph does not take into consideration the error seen in the charring rates, if taken into account only test 1 is considerably below from what is expected on the Eurocodes.

4.4 Visual analysis on the mechanical fasteners and the plates

After examining the timber members further analysis was done on the other components of the joints, the plates as well as the fasteners. Just like described before these components did not need much force to been pulled from the timber for the first three tested assemblies.

In the picture below is possible to see one of the plates-fastener systems after a test, in here we can see that there was no major deformation in the exposed plate, and that the char was able to encompass the exposed nails, this was the case for all configurations except for the protected one where the base materials only showed small discoloration around the nails.

Figure 33.Plate and fasteners extracted from the test 1

Although there were no major deformation samples 1, 2, and 3 showed a slight warping following the contour produced by the bending created by the moments generated by the jack system (see Figure 19). Additionally, these plates were measured after the test to see whether there was any elongation during the application of the forces, and for all samples no increase in the length or width was reported.

The same procedure was done with the fasteners, their dimensions were measured as well as their angle and compared to the unaffected fasteners, this showed almost no deformation in the nails, most of the changes that did occurred were the oxidation and the deposition of a soot layer surrounding the fasteners for the samples 1, 2 ,and 3, this is represented in the next figure.

Figure 34.Fasteners after being exposed to the ISO 834 curve, from test 1, 2 and 3 (from top to bottom)

One of the differences that is noticeable between the screws and the shank nails used is their difference in regard to their mass, being the nail almost as twice as heavy as the self-tapping screw (4.1 grams vs 2.2 grams). To see any possible changes caused by this in the interaction of the fastener towards the charring of the member the visible marks left after the removal of the joints were inspected, this can be seen in Figure 35.

Figure 35.Pictures of the jointed area showing marks from the mechanical fasteners, Test 2 using nails (upper picture),and Test 3 using screws (bottom picture)

In the last figure is possible to observe that for the nails used for test 1, and 2 the marks left after the removal of the fasteners were wider while for the screw the holes were more narrow and deep, these marks were only visible in the last cut of each sample as for the cuts closer to the gap had a deeper charring than the fasteners themselves.

To see the influence of the size and type of fastener a linear steady state heat transfer simulation on Inventor Nastran was made (Figure 36), for this the two types of fasteners used, the shank nail and the self-tapping screw, these were modelled according to their dimensions and physical characteristics, then a steady temperature (600°C) was applied to the exposed side and a convective environment at room temperature (17°C) covered the whole nail, in this case a unrealistically high convective heat transfer was used as to make clearer the behavior difference among the two fasteners. This simulation was done only as a severely limited analysis to show the expected behavior rather than the real one, since it does not take into consideration conduction within the wood, pre-heating, the evaporation of water within the wood, etc.

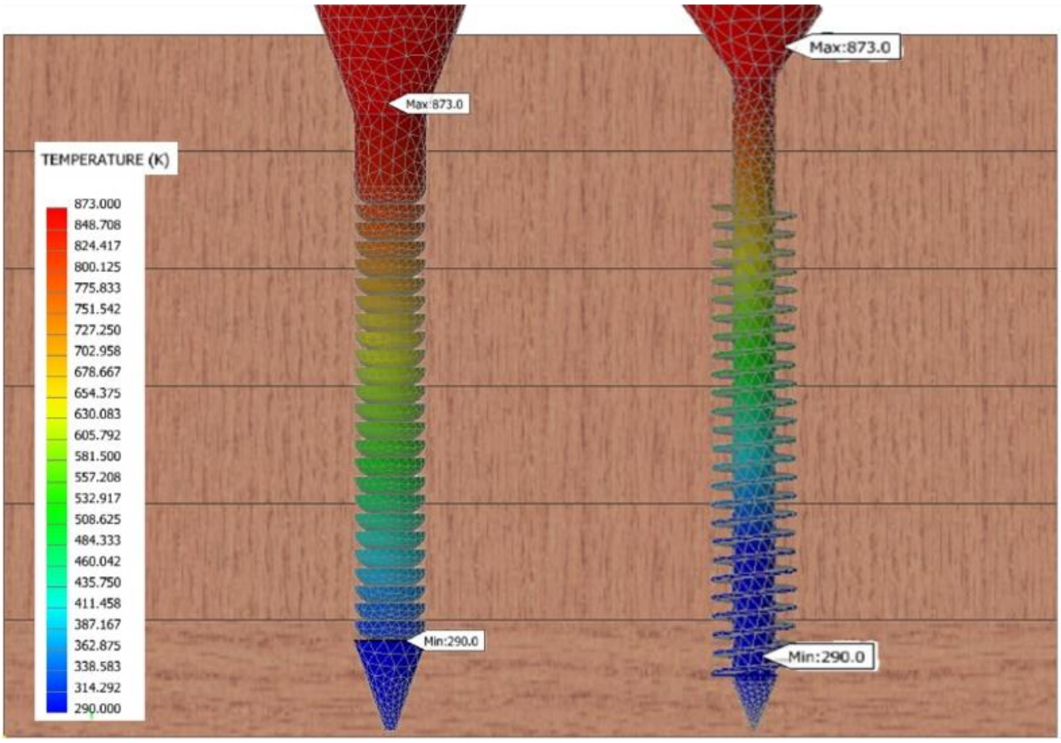


Figure 36.Linear steady state heat transfer of the two fasteners on a highly convective environment showing the temperature gradient (°Kelvin)

As the previous figure shows the temperature on the more massive nail was more constant across the nail, carrying more energy to the bottom, on the other side we see a faster “drop” on the energy for the narrower nail on the account of a bigger area of exposure to the colder environment and the smaller amount of material to retain the heat.

The shank nail by having about twice as much mass, will be able to carry more heat across it surface and dissipate more of the heat under a larger area of it surrounding when exposed to the same heat influx than the screw, this means that the energy has a better chance of dissipating before the charring starts, none the less this also mean that the rest of the surrounding wood will preheat faster and as more of the fastener is exposed to the heat more energy will be carried through the nail allowing for more charring as the time of exposure increases.

This phenomena is directly linked with what is seen in Figure 35, in the section with the nail the mark left during the test had a bigger area, possibly due to the bigger amount of energy carried by the shanked nail to the glulam at the final moments of the test, consuming and pyrolyzing more material than the screw .

After analyzing the behavior of the exposed fasteners the protected join was also studied, as was mentioned before the charring did not significantly occurred below the plate, none the less sign of discoloration were observed close to the surface of the holes but were not noticeable in the deepest sections of the bores. Much like in the simulation this shows that the temperature in the fastener does not remain relatively constant instead it dissipates more heat in the areas closer to the source of heat.

Figure 37.Bores in the 4th test showing discoloration

4.5 Displacement of the joints

The size of the top gap was measured during the testing as to see any possible displacements due to the loss of strength of the assembly, the results of this were compiled in the next graph next to the time of measurement.

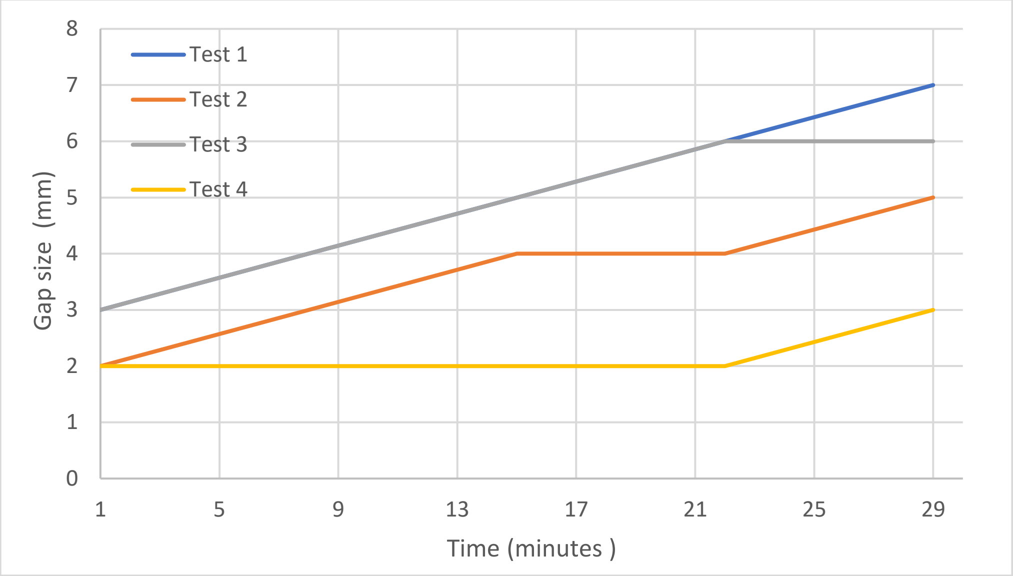


Figure 38. Top gap size measurement during the fire exposure

It is possible to see in the previous figure that there was an increment of the gap size for all samples, the biggest increment of length in the gap was for sample 1, which had an increase of 4 mm during the testing, this increase was followed by the samples 2 and 3 which showed an increase of 3 mm each, finally the protected sample had an increase of only 1 mm by the end of the test.

Something important to mention in regards to these measurements is that the gap size did not stayed constant trough the gap, meaning that the top size was bigger than the bottom, this was the expected behavior as the system used generated more powerful tensile forces on the top due to the eccentricity of jack over the sample.

There are several factors that can explain the increase of the gap: the displacement of the fasteners, the elastic or plastic deformation of the plates and the thermal expansion.

Due to the length of the test and the lack of intact subtract of the fasteners the displacement of the fastener was not possible to be recorded during the test, as for the elastic deformation since the force was applied during the beginning of the test it is unlikely for it to be the main contributor in the increase in the gap, finally the plastic deformation could be disregarded as the difference in dimensions on the plates and the nails were not significative enough as to point the occurrence of it.

This leaves the thermal expansion as the main measurable contributor on the increase of the gap, the Eurocode 3 [67] assigns different expansions for steel depending on the temperature, as for the tested samples the maximum temperatures of the plates surpassed the 700ºC meaning that the expansion followed the next relationship.

$$\frac{\Delta l}{l} = 1.1 * 10^{-2} \quad for\ 750°C \leq T \leq 860°C$$

Considering that the plates were of a length 200 mm this means that the exposed plates had an elongation produced by the thermal expansion of 2.2 mm by the end of the test, which could account for a large part of the widening of the gap for the unprotected samples.

4.6 Mechanical performance of the samples during the ISO834

By having the charring rate as well as the temperature in the joint is possible to calculate the overall strength of the tested joint at a given time during the testing, for the resistance of the plates the yield strength of the steel can be calculated using the temperature and the relationships laid out in the Eurocode 3 [67], after this the yield strength along the size of the plates can be used in conjunction to find the force needed for yielding.

These values were calculated for test 1, 3 and 4 and portrayed in graphs along with the force needed for the withdrawal of all the fasteners within the plate and the idealized tensile force that the lower sections of the samples are exposed to during the testing. These graphs along a description of their observed behavior can be seen next.

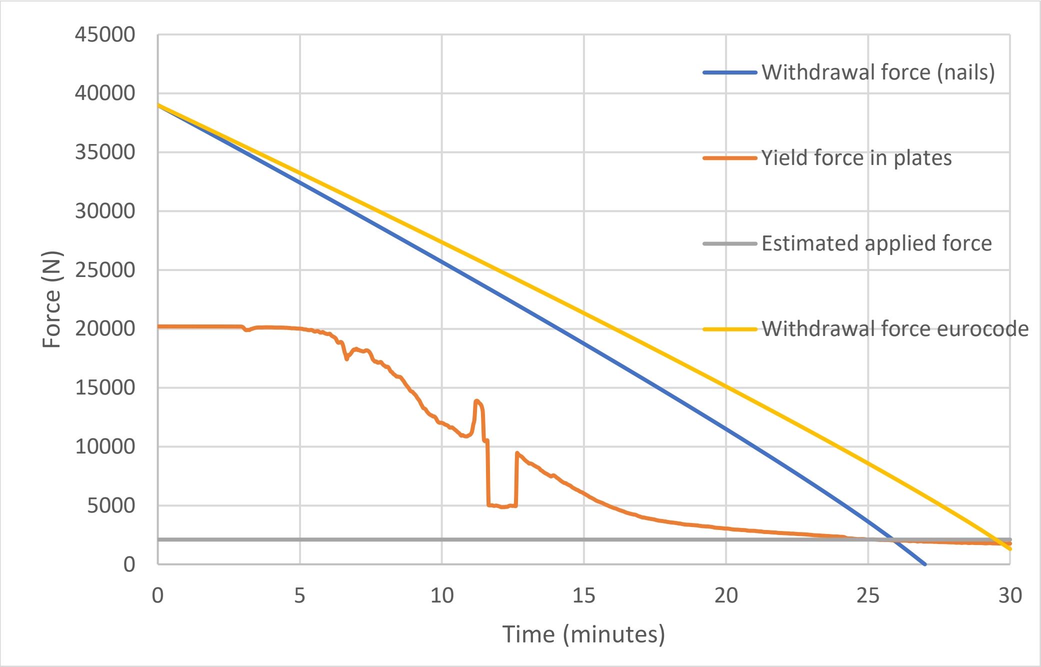


Figure 39.Yielding, withdrawal, and applied forces during the ISO 834 for test 1

In Figure 39 we can see the forces necessary for what would be considered failure in a mechanical assembly, either the release of the mechanical fasteners or the yielding of the exposed plates. Just like it was seen in Figure 32 we can see the pullout force reduction due to the losses in the effective depth of the nails, in this case however it is also possible to see and compare how the yielding force is also diminished during the testing.

As for the yielding force we can see it follows an almost inverse behavior to the one of the temperature recorded in Figure 23, the reason of this is that as is stated in the Eurocode 3 steel reduces its mechanical capabilities with the increase of temperature, during the first minutes of heating this change is not very noticeable before 300 ºC as steel still holds most of its characteristics.

After this the strength of the plate decreases steadily until a large dip in the yielding strength is seen when 10 minutes have passed and the thermocouple records the dip and a sudden increase of temperature discussed in section 4.1, this loss of strength from minute 11 to 12 however is unlikely to be as severe in the real world as the steel would have some thermal inertia opposing such abrupt changes, is worth mentioning that the temperatures recorded were taken directly in the steel plate-glulam interface where changes in the temperature could have being more sudden than in the steel itself.

The loss in the yielding strength reaches the applied force at around 24.8 minutes and close to a minute before the withdrawal total loss of strength, meaning that by this time the joint was being held down mostly by the upper plate.

In the former picture the loss of mechanical resistance due to the loss of timber in the unjointed area was not added as the values for resistance in tension for cold conditions and during the fire scenario are much higher. This is portrayed in Figure 40.

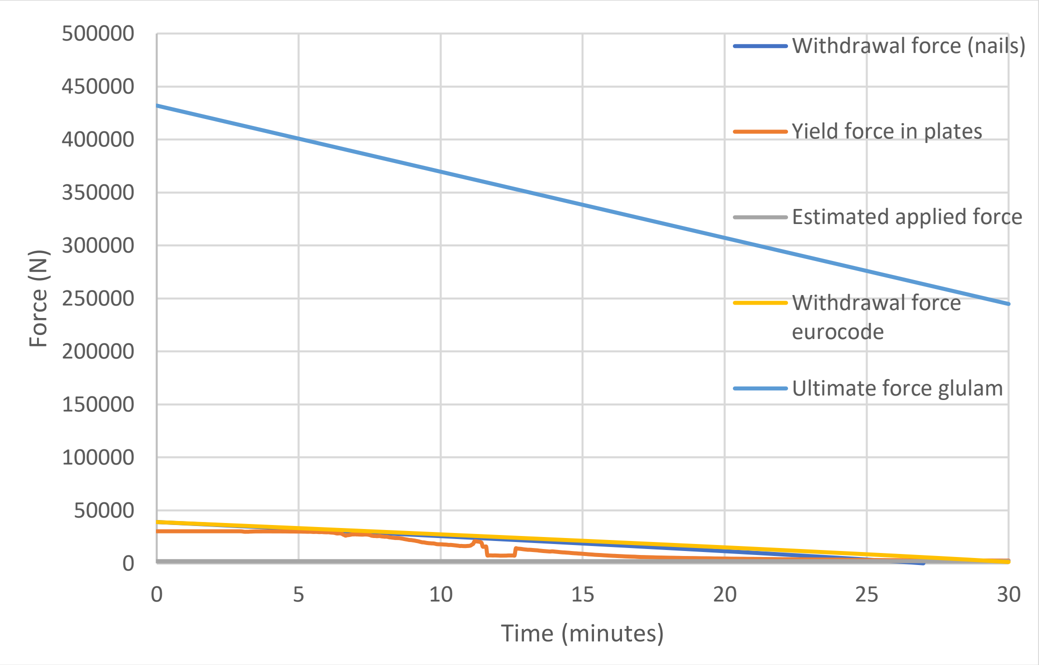


Figure 40.Yielding, withdrawal, glulam tensile failure, and applied forces during the ISO 834 for test 1

When compared to the loss of strength of the samples due to the reduction of the timber area it is possible to observe that the reduction of it is linear and at lower pace that for the plates and the mechanical fasteners, for example by minute 15 glulam remains at 79.5 % of its strength while at the same time the total withdraw force was at 49.5 % of his maximum and at 28.59 % for the plates. This signals that in this setup the point of failure would be the joints not only due to the smaller overall resistance but also the speedier loss of their mechanical attributes during heating.

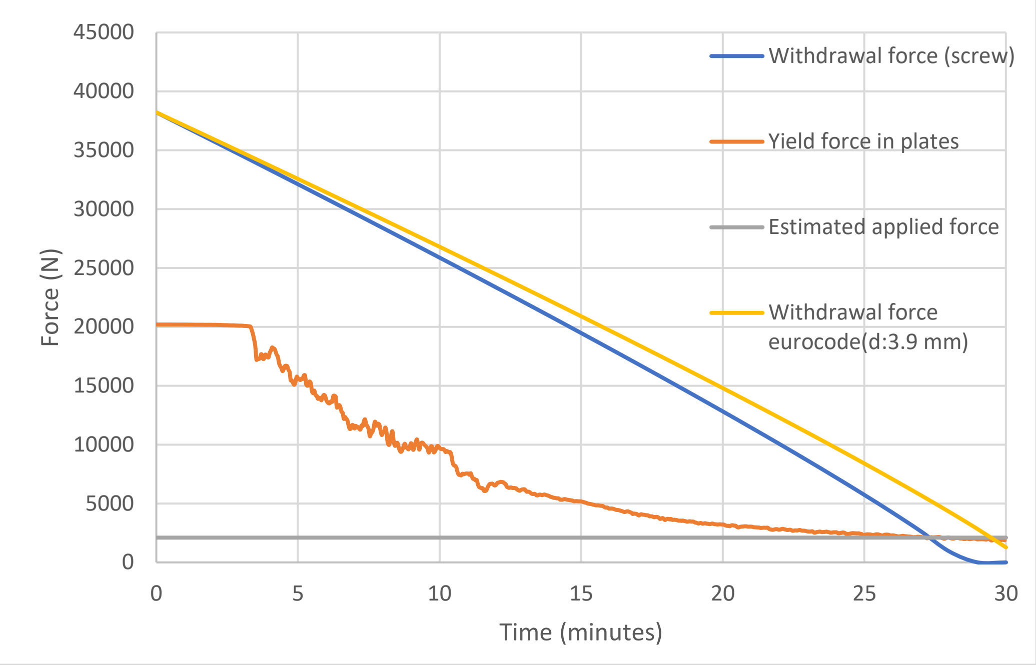


Figure 41.Yielding, withdrawal, and applied forces during the ISO 834 for test 3

As for the third test the yielding strength much like for the first test remained almost constant during the first minutes of the curve, then it also saw a most of its lost on the strength of the plates before half of the test had passed keeping 25.44% of its strength at 15 minutes.

Although the lost in strength during the beginning of the test was more severe for the 3rd test it took longer for the plate to reach the idealized applied force, 26.5 minutes instead of the 24.8 minutes in the first sample.

For both unprotected setups the system failed before the end of the testing so as to compare the effect of protection on the mechanical resistance the same graph seen in the last two figures was made but taking into consideration the values in temperature and charring from the 4th test.

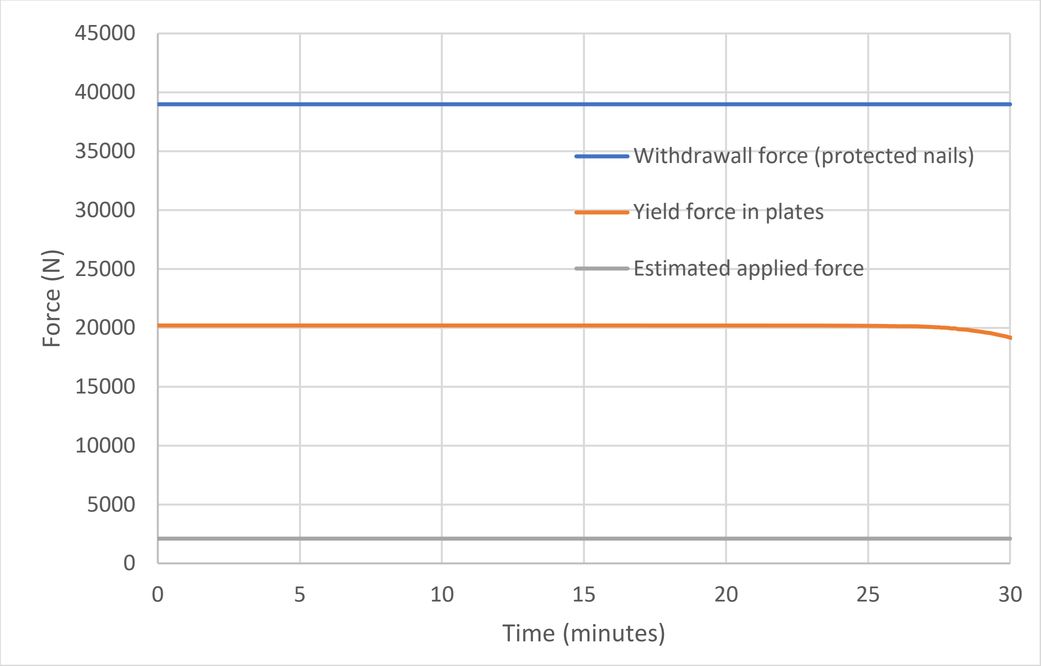


Figure 42.Yielding, withdrawal, and applied forces during the ISO 834 for test 4

For the protected samples the force of withdrawal was kept constant during the 30 minutes that the test lasted, as there was not visible charring under the fasteners, none the less the discoloration present in some of the area around where the fastener was present could signal some loss of the embedment strength, for the purpose of this test however these losses were not considered.

As for the yield strength of the plate it is possible to see than the board of gypsum kept the temperature of the plate under 300 ºC for most of the duration of the testing making the mechanical losses in the joint almost imperceptible until 28 minutes from the test start, keeping 95.7 % of its yielding strength by the end of the first 30 minutes.

5 Analysis and discussion

The previous chapter of this work described the results obtained from the application of an ISO 834 fire curve on a mechanically loaded glulam-joint system, it is the purpose of this chapter to analyze and contextualize these result as to understand their implications on the fire performance.

To facilitate this, various sub-sections will be made describing a particular aspect of the results like the charring rate, the fire performance, and the effect of fire protection.

5.1 Charring rate in the tested glulam configuration

In Table 1 (seen on page 46) the charring rate of unjointed areas of the samples was reported as 0.76±0.07 mm/min, in literature a glulam beam with a similar density that the tested samples (464 kg/m3) exposed to 60 minutes of the ISO 834 curve had a charring rate of 0.781 mm/min [33], as for the Eurocode glued laminated timber with a characteristic density of 290 kg/m 3 or more have a notional design charring rate that is tabulated as 0.7 mm/min[59].

Considering the error margin of the result obtained through experimentation during the making of this report is possible to see that it adapts quite well to what is reported in literature, but although this charring rate followed what was reported, the charring rate on all unprotected joints, 1.3±0.1 mm/min, 1.16±0.07 mm/min and 1.23±0.13 mm/min for test 1 ,2 and 3 respectively, surpassed slightly the 1.5 safety factor given by the Eurocodes.

Other studies on fire performance of joints have also showed a severe increase of charring in the area of the connection, one example of this is given by A. Frangi [68], showing charring rates of 0.7 mm/min close to the connection and charring rates up to 1.2 mm/min on the joint itself.

The increase in charring could be influenced due to myriad of circumstances such as the heat conduction from the fasteners, the perforation of the charred area that can reduce the protection of the charred layer, the mechanical efforts in tension or compression leading into the crushing of wood or the charred area(exposing more material to the heat), and round-off effects near the gap [69].

Due to the limitations in the experimental setup showing the influence of each of these aspects on the charring rate will be out of scope, none the less, one of the objectives of this report was to measure the effect of different configuration on the fire performance. In the case of the choice of fastener the experimental data showed a smaller area of charring for the less massive fastener, the self-tapping screw.

Although the screw and the nail possess similar diameters, 4 mm vs 3.9 mm, the fact that the internal shaft of the screw was significantly smaller meant less mass, 4.1 vs 2.2 grams, and less heat transferred onto the material which translated in the testing as a reduced amount of charring surrounding the fasteners.

These results are comparable to those reported by Hofmann [70], in in which different self-tapping screw configurations were tested while embedded in glulam, among the result a strong relationship was found on the pull out resistance of the fasteners vs the diameter and length, displaying that narrower and longer embedded screws kept their mechanical attributes for a longer amount of time when exposed to a heating curve as the surrounding timber heated up more slowly.

One thing to consider is that Hoffmann's results as well as the ones displayed in this report make use of fire curves that last more than 30 minutes, is possible that during the first minutes of a fire or in the case of protected fasteners that more massive fasteners could act as heat sink delaying the superficial charring around the fasteners[69].

Another aspect that was studied in this report was the influence in plate size, as for the charring rate the use of a bigger plate resulted in a wider area of charring surrounding the joints but with a smaller depth, meaning that the bigger plate distributed the heat more evenly across the surface of the material or somewhat delayed the pyrolysis process by diminishing the amount of oxygen exposed to the underlaying timber.

This results somewhat resembles the ones showed by Aarnio and Kallioniemi [69] in which the use of unloaded steel plates created a reduction on the charred area during the first 15 minutes of the testing, but produced no differences after 60 minutes of the ISO 834 curve. The reduction on the influence of the plate size with time could be due the charring of the material underneath that prevents an efficient heats transfer or the presence of cracks on the char that allows for the escape of pyrolysis gases and the burning of the material.

An aspect that was not studied due to the limitations on the amount of experiments was the use of different spacing to observe its effect on the localized charring of the joints, however its overall behavior could be estimated. An increase in the separation between the fasteners would mean a bigger area of heat dissipation for each of the fasteners delaying in this way the concentrated pyrolysis produced in the jointed area. This is somewhat considered in the Eurocode 5 [23] where a minimum distance among fasteners are advised as to ensure a proper embedment.

5.2 Fire performance of the tested samples

All the unprotected samples suffered significant losses in their mechanical behavior due to the heating of the plates as well as for the reduction in embedment produced by the burning of the subtract, in the Eurocode [67] as was mentioned in chapter 2 there are design recommendations that assign the fire resistance of unprotected fasteners to 15 minutes and up to 30 minutes with some additional provisions, for the three unprotected samples by 15 minutes the withdrawn strength of the fasteners was close to half of its total strength and considering that larger fasteners can be used this provision does not seem under conservative.

In the case of the plates the losses were more severe retaining about a quarter of its yielding strength by this time so under a normal load the setup could yield making the structural element fail; for this reason, the Eurocode advices the use of embedded connectors on wood to wood connections.

Previous studies on unprotected SWS members with glulam made by Peng [71] showed failure times of 14 minutes for load ratios of 10% and of 8.5 minutes for load ratios of 30 %, due to the decoupling of the joints caused by the elongations of the holes in which the fasteners were imbedded.

While in this report the failure time was not studied in detail, by watching the sudden spike in temperature on Figure 23 one can assume that by 12 minutes the exposed section of the structural element went through a significant change that could possibly mark its mechanical failure, as by that time the smoke was running freely through the gap and heating the upper plate. This assumption would match quite well the results provided by Peng.

Much like in the last subsection some observations can be made on the different configurations and their influence on the fire performance, in the case of shank nails the performance seemed to be poorer than the one provided by the self-tapping screw as the withdrawn strength dropped faster than for test 3 even considering the smaller initial withdrawn strength of the screws.

As for the bigger plates the result conformed better to those provided by the Eurocodes as seen in Figure 32, and since for test 1 and 3 the delimiting factor for failure was the yielding strength on the plates it seem to be best practice to increase the area of the plates used, not only to delay the charring on the jointed area but also to increase the yielding force needed for failure.

The fire performance of timber elements does not depend solely on their ability to keep their mechanical attributes during a fire, as was described in chapter 2 integrity and insulation are as important when it comes to ensure the safety of the dwellers in a building. For these two characteristics the ability to contain smoke and heat from one enclosure to another is fundamental and in the case of joints, the size of the gap among members can be one of the main drivers in the leakage of heat and smoke.

During the testing all the samples showed gaps sizes below 3 mm in the beginning but in the case of the unprotected joints these sizes increased by 4 mm for the first test and by 3 mm for the second and third test. The size of the gap was an apparent driver of heat through the sample as the bigger size on the gap led to more charring in the interface as seen in Figure 29. The charring in the gap is not the only problem as we can see after minute 15 in Figure 23 the temperatures rise above what is accepted for EI, making the joint fail in this aspect before the end of the test.

Studies have shown that gaps should be kept at size smaller than 5 mm the to prevent charring[43]. In the case of the first 3 tests this size was surpassed before the end of the 30 minutes even at the relatively small load that was applied onto the system, in the case of bigger loads this number would more than likely be bigger which in turn would result in more charring in the jointed area and more propagation of heat and smoke trough the gap.

This increase in the size of the gap is reported for laminated veneer by T.Chuo [72], which did not only reported an increase due to the elongation of the elements of the joint but also due to the crushing of the char produced by the movement of the fasteners.

5.3 Fire protection on the fire performance of the joints

Among all the test performed the one that was protected using gypsum had the best performance, the lack of charring under the plates meant that the withdrawal strength of the material remained almost the same during the testing , additionally by keeping the temperature during most of the testing below 300 degrees the yield strength of the plates was almost unchanged until the last minutes of the testing.

Some other benefits of the protection were the reduction on the size of the gap while exposed to the fire curve, and by doing this it keeping smoke from propagating through it, finally the temperature during the heating of the furnace followed more closely the one of the ISO, the reason for this is that less timber was exposed to the fire delaying in this way the amount of heat released by the exposed glulam.

Most research covering the effects of gypsum protection on joints has also shown it to be a great tool to increase the fire rating and to prevent permanent damage in case of a fire, Frangi [68] reported that for bolts in glulam members the use of a 15 mm gypsum board lead to an increase of fire resistance of 27 minutes, these values are also similar to the ones reported by Buchanan of 30 minutes of protection in joints for 15.9 mm of gypsum[73].

Comparing these results to the unprotected samples shows that in cases where safeguarding a building or people is a priority the protection of essential joints is best practice as it can ensure a reliable fire resistance. As was seen for the unprotected samples is not enough to assume a resistance of 15 minutes for fasteners, the big variability of joints configurations could cause a faster failure under certain circumstances, by protecting those configurations with an element that has a certain value of resistance like gypsum, the behavior of it, while the protection last, becomes more predictable.

5.4 Relevance of the results regarding the main objectives of this work

In section 1.2 the objectives of this work were mentioned, and through the rest of this document experiments as well as literature research were done to tackle them in a meaningful way.

The first of these objectives was to observe and record the behavior of several GLT- joint systems under a load and the ISO fire curve, this was achieved through constant monitoring of the samples during the experimentation and by transcribing what was thought to be the most relevant data, and this information then was compared to relevant results from available literature.

The second objective was to study the mechanism of failure of the system and providing information about the main sources of it. Through the study of the charring pattern of the samples, the temperatures in the jointed area and visual inspection, it was seen that the most likely source of failure was the yielding strength of the plates as it was the most susceptible to high temperatures. This however would not be the behavior for every type of joint and load since a different configuration could mean a different weak point.

Another goal was to provide information on the effects produced by the change of some parameters over the performance of the joint, the four different configurations showed significant differences on the behavior when it come to the change of some parameters like fastener size, plate size and the use of protection.

As for the final objective collecting data to provide recommendations that could improve the fire behavior of buildings using glulam. The recorded influence caused by the size of fastener and plate on the charring behavior showed patterns that could in turn be interpolated into design choices, a larger quantity of narrower fasteners could be chosen instead of a smaller quantity of bulkier fasteners as this could in turn increase the fire resistance of a member. More significant than this was the efficacy of fire protection to keep the mechanical attributes of the joints.

6 Limitation of the results

The main purpose of this work was to test different configurations and see their influence on the fire performance of joints, this entails that the more tests were done the more factors and their influence could have been analyzed.

Due to the limitations in the availability of the equipment used only 4 different configurations were tested although 8 different assemblies were originally planned, the lack of these additional experiments meant that the scope of this report was reduced significatively and only 3 different aspects were studied (influence due to : type of fastener, plate size, and protection).

The lack of equipment also meant that none of the 4 experiments performed could be repeated using the same configuration as to see the repeatability of the results and in case the repeatability was poor the possibility too look for possible problems in the experimental setup that could have caused it.

Since no traditional tensile testing could be applied in the available furnace a new setup was designed using a hydraulic jack system, this brought a series of variables that could affect the obtained results, some of these were:

- The eccentricity in the forces provided by the hydraulic jack generated a series of moments and external forces that makes the results more difficult to compare to those reported in literature using more conventional setups.
- Unlike common tensile testing the pressure was kept manually, this generated some fluctuation in the forces applied.
- For the testing the simplifications of a homogeneous force distribution across the joint was used, this simplification however is not entirely accurate and most likely skewed the results.
- The lack of displacement sensors to measure the size of the gap meant that the measurements of the gap were taken more sparsely and with less precision, this could add a significant error in the measurements taken
- The top of the oven where the joints were tested was not completely sealed off during the test, meaning that there was a constant flux of gases through the gaps of the setup. This movement could have caused certain variations in the heat distribution while the ISO 834 test was performed, the resulting variations could make the results less comparable to tests made in previous research that make use of ovens with a possibly more homogenous temperature profile.

Most of the results showed in this thesis were comparable to those seen in literature which points to the results having some validity, however timber products including glulam possess a great variability of properties due to their manufacture, storage, and installation. This means that even for the same configuration results could change somewhat from test to test, taking this into consideration further analysis is necessary before applying or considering the findings of this document, and even then, the caveats previously mentioned should be considered.

7 Summary and conclusions

In this report several different configurations of joints were tested for glulam members. Loads of around 4.2 KN were applied across the material while they were exposed to an ISO 834 curve, the results and analysis of the experimentation were laid down in chapter 4 and 5. From these sections the following conclusions were drawn:

- The loading system created for testing the samples gave comparable results to those obtained in literature.
- In glulam structures the joints could be considered a weak point in fire conditions as their strength is more susceptible to high temperatures.
- The gypsum protected joint was able to keep most of its mechanical attributes during the fire testing
- The type of failure was bound by the load applied, as the yield strength of the plates and the withdrawal strength of the fasteners behaved differently during the fire testing.
- The use of more massive fasteners can lead to more charring around the fastener under certain conditions.
- Using a bigger plate showed a more homogeneous charring at the joints, which lead to a decrease in the losses of withdrawal strength during the fire testing.
- The charring rate in the unprotected joints was reported to be bigger than the overall charring rate of an element multiplied by the safety factor provided by the Eurocode. With a maximum difference of 14% increase on the charring rate for the first test.
- More tests should be performed checking the behavior of joints under fire conditions to confirm if the safety factor given by the Eurocode is conservative enough. If not, attempts should be made to revise this number as to ensure proper levels of fire safety.
- The observed behaviors from the tested samples resembled to some extent the results from previous research when it comes to :the differences in charring rate in jointed area vs unjointed, the smaller amount of charring with less massive fasteners and the efficacy of gypsum as fire protection .

Although the scope of this document was not able to cover as thoroughly how different configurations of glulam joints affect the fire behavior, it was able to show a clear picture on the importance of choosing the right configuration of a joint when designing, as a simple variable like type of fastener can have a huge influence on the performance of a joint.

8 Further research

The great variability in joints makes it almost impossible for a single research work to cover most of the possible configurations, additionally different timber substrates could generate even more variability in the results.

Due to this, it seems relevant to continue investigating and expanding the knowledge covering timber joints and their behavior towards fire; some of the areas that could be expanded on are:

- Some of the planned test that could be not performed had the purpose of recording the effect on the distance between the fasteners in the plate, the angle of embedment in the fasteners, distance of the fasteners to the gap, and the use of angles instead of plates. Further studies covering these topics could make the understanding of different joint configurations more complete.
- Glulam is a material that has been used for many years so it has been studied more thoroughly that other materials such as CLT, making similar testing on less researched timber products could provide very useful information.
- Additional inclusions in the used setup could improve future tests, the addition of displacement sensors, thermocouples in the fasteners and an electric pump could give more precise and complete results.
- As was mentioned in literature the behavior of the ISO 834 fire curve does not follow the behaviors of a conventional fire, this creates a gap between the results produced by it and the consequences of a real-life fire. Further analysis of these joint or other configurations could be done using more “natural” fire curves with the objective of having a better understanding under real conditions.

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10 Appendix

Hydraulic force calculation

To calculate the force for the hydraulic jack the next calculations were done:

$$pressure\ applied\ by\ the\ jack = 80\ bar = 8\ Mpa$$

$$force\ applied\ by\ the\ jack = pressure * area\ of\ the\ jack$$

$$Fj = 8\ \frac{N}{mm^2} * 26^2 mm^2 * \frac{\pi}{4} = 4.25\ KN$$

Different zones used to measure the charring rate

For the charring rate measurement two different zones were measured one just below were the plate and the fasteners were installed (represented by blue in the next picture) and the section that was exposed but did not had any fasteners or joint attached.