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Fire Behaviour and Fire Stability Test of Wood Species and Joint Types

Maria Binte Mannan

Supervisor: Prof. Dr. Patrick van Hees

Lund University, Sweden

Secondary Supervisor: Prof. Dr. rer. nat. habil. Bernhard Schartel

Federal Institute for Materials Research and Testing (BAM), Germany

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Disclaimer

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Maria Binte Mannan
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Maria Binte Mannan

Fire Safety Engineering
Lund University
Sweden

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Abstract

The construction industry has shown a significant interest in timber due to its sustainability, leading to widespread use. However, choosing the ideal material can be challenging due to the varying performance of different types of wood, especially considering its combustible nature. Besides, the joints in the timber structure are considered the weakest part of the structure. The physical separation in the wooden jointed sample due to the fire is termed here as the failure of the sample in other words the stability of the sample. In the current state of the art, the failure is influenced by the behaviour of the wood under fire, along with cracking, and opening occurring due to the jointed glue line. Therefore, in this study, an experimental investigation has been performed focusing on two major goals - to understand the behaviour of the jointed wood in developing fire and to understand the stability of the jointed sample under fully developed fire. To study this behaviour, in total 160 small-scale tests were performed, where 100 cone calorimeter tests and 60 fire stability tests were performed. Three different types of wood namely Pine, Spruce, and Beech, and 5 different joints (no joint, butt joint, half-lap joint, 3-finger joint, and 6-finger joint) were analysed. Also, two different thicknesses 24 mm and 42 mm of Spruce wood were evaluated. Besides, in the cone calorimeter test, three different heat flux levels (35, 50, & 65 kW/m2) were tested as part of the thesis work. From these tests, the changes in the fire behaviour were observed for three different woods in the second peak heat release. Cracks and deformation during the burning were noticeable influential factors. The method developed in this work is suitable for observing the failure time. Nevertheless, there are some limitations to this approach. The failure in the jointed timber has been observed mostly from the glue line. The thermal penetration through the sample and charring rate are indications of this phenomenon and are considered as important tools for understanding the failure of the sample. Even so, none of the investigated features alone showed the same effect on the heated depth as that observed in the experimental study. This highlights the need for further research to understand the mechanisms causing the failure of the jointed wood.

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Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.brand.lth.se

Telephone: +46 46 222 73 60

Abstract

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Abstract in Mother Tongue (Bangla)

কাঠের স্থায়িত্বের কারণে নির্মাণশিল্পে এর গুরুত্বপুর্ণ আগ্রহ লক্ষণীয়, যা থেকে এর ব্যাপক ব্যবহার শুরু হয়েছে। তবে, আদর্শ উপাদানের নির্বাচন করা কঠিন হতে পারে কারণ বিশেষত তার দাহক স্বভাবের বিবেচনায় বিভিন্ন প্রকারের কাঠের বিভিন্ন কার্যকরী কর্মক্ষমতা বিবেচনা করা যায়। পাশাপাশি, সংযুক্ত স্থানগুলোকে কাঠনির্মিত স্থাপত্যের সবচেয়ে দুর্বল স্থান বলে মনে করা হয়। এখানে, নমুনার ব্যর্থতা বা স্থিতিশীলতার মাপকাঠি বলতে আগুনের কারণে সংযুক্ত কাঠের আলাদা হয়ে যাওয়াকে বোঝানো হচ্ছে। বর্তমান প্রযুক্তিতে, স্থাপত্যের ব্যর্থতা আগুনের প্রতি কাঠের আচরণের মাধ্যমে প্রভাবিত হয়, পাশাপাশি ফাটল এবং আঠা দ্বারা সংযুক্তির রেখা খুলে যাওয়াও অন্যতম। সুতরাং, এই কাজের মধ্যে দুটি মূল লক্ষ্যের দিকে খেয়াল রেখে একটি পরীক্ষামূলক তদন্ত সম্পন্ন করা হয়েছে - সদ্য লাগা আগুনের মধ্যে সংযুক্ত কাঠের আচরণ বোঝা এবং পরিপুর্ন আগুনের মধ্যে সংযুক্ত কাঠের স্থিতিশীলতা যাচাই করা।

এই আচরণ অধ্যয়নের জন্য, মোট ১৬০ টি ছোট মাত্রার পরীক্ষা পরিচালনা হয়েছিল, যেখানে ১০০ টি কোন ক্যালোরিমিটার পরীক্ষা এবং ৬০ টি আগ্নি স্থিতিশীলতা পরীক্ষা হয়েছিল। তিন প্রকারের কাঠ, যারা পাইন, স্‌প্রুস, এবং বিচ নামে চিহ্নিত হয়েছিল, এবং ৫ ধরনের যোগস্থান (যোগস্থান নয়, পিঠ যোগস্থান, আধ-ল্যাপ যোগস্থান, ৩-আঙ্গুল যোগস্থান, এবং ৬-আঙ্গুল যোগস্থান) বিশ্লেষণ করা হয়েছিল। এছাড়াও, স্‌প্রুস কাঠের দুটি বিভিন্ন মোটায় মাপ (২৪ মিমি এবং ৪২ মিমি) মূল্যায়ন করা হয়েছিল। এছাড়াও, থিসিস কাজের একটি অংশ হিসাবে, কোন ক্যালোরিমিটার পরীক্ষায়, তিন ধরনের তাপসংক্রান্ত স্তর (৩৫, ৫০, এবং ৬৫ কিলোওয়াট/মিটার^{২}) পরীক্ষা হয়েছিল। এই পরীক্ষাগুলি থেকে, বিভিন্ন কাঠের জন্য দ্বিতীয় উত্তীর্ণ তাপমুক্তি পরিবর্তনগুলি দেখা গিয়েছিল। অগ্নিদাহের সময় ফাটল এবং স্থানচ্যুতি কে গুরুত্বপূর্ণ প্রভাবশালী উপাদান হিসেবে খেয়াল করা গেছে। এই কাজে উদ্ভাবিত পদ্ধতি বিফলতা সময় দেখতে যোগ্য। তবে, এই পদ্ধতিতে কিছু সীমাবদ্ধতা আছে। সংযুক্ত কাঠের ব্যর্থতা মূলত আঠার লাইন থেকে দেখা গিয়েছিল। নমুনার মধ্যে তাপের প্রবেশ এবং কয়লা উৎপন্ন হওয়ার হার এই বিষয়ের সত্যতা প্রমান করে এবং এরা নমুনাগুলোর ব্যর্থতা বোঝার জন্যেও ভাল নির্দেশক। এরপর ও যেকোন একটামাত্র বৈশিষ্ট্য থেকে পরীক্ষামূলক কাজের সমগ্র প্রভাব লক্ষ্য করা যায়নি। এই ঘটনা এই বিষয়কেই জোরালো করে যে সংযুক্ত কাঠের ব্যর্থতার কারণ বুঝতে ভবিষ্যতে আরো গবেষণার প্রয়োজন ।

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Notation

Terminology

k - Thermal conductivity (W/mK)

Q - (kW/m^2)

T - Temperature (°C)

t - Time (s)

Greek letters

α - Thermal diffusivity (m^2/s)

ρ - Density (kg/m^3)

Acronyms

GLT - Glue-laminated timber

CLT - Cross-laminated timber

HRR - Heat Release Rate

MUF - Melamine-Urea-Formaldehyde

PRF - Phenol-resorcinol-formaldehyde

PUR - Polyurethane

THR - Total Heat Release

MLR - Mass Loss Rate

EHC - Effective Heat of Combustion

Chapter 1 Introduction

Timber structures have recently regained renewed interest within the construction industry, driven by a growing emphasis on sustainability and environmental awareness. Beyond its eco-friendly characteristics, timber's appeal extends to its capacity for rapid on-site assembly and its potential suitability for multi-story constructions [1]. However, in construction practices, the utilization of engineered wood products like glued-laminated timber (GLT) and cross-laminated timber (CLT) often necessitates the use of joints to connect various timber components. Longitudinally joining timber pieces with adhesive has been acknowledged as a reliable and cost-effective method for producing high-quality timber sections of the desired length and for minimizing timber wastage [2].

Currently, a variety of joints are employed in timber construction, including nailed, bolted, screwed, glued, glued-in-rod, and large-finger joints [3]. Furthermore, solid wood components are interconnected using different joint types such as butt joints, half lap joints, or finger joints [4]. Finger jointing allows for the elimination of undesirable timber sections, thereby enhancing both the strength and aesthetics of the timber product. Consequently, finger jointing stands out as an efficient method for enhancing the operational effectiveness of sawmills by reducing timber wastage [5]. Despite the extensive research conducted on various aspects of timber engineering, including wood properties, structural design, and construction techniques, a significant gap remains in the comprehension of glued timber joints.

The behaviour of wood under fire is influenced by numerous factors, including its moisture content, chemical composition, geometry, and density, as well as external conditions like heat intensity and flame proximity [6]. These factors collectively determine how wood ignites and burns. Wood, primarily composed of lignin and cellulose, undergoes a distinct process when exposed to fire, marked by the formation of char. After pyrolysis, heat exposure ignites the wood surface, causing the first peak in Heat Release Rate (HRR), which initiates pyrolysis in the unburnt wood and thus releases the volatile gases. Continued combustion sustains pyrolysis, leading to the generation of additional volatile gases. However, as the char layer develops, it acts as insulation, slowing down the pyrolysis process and impeding heat and gas transport through the material, resulting in a decrease in HRR. The second peak in HRR occurs when the char layer reaches the rear part of the sample, allowing further volatile gases to escape and contributing to the fire dynamics [7]. Understanding these mechanisms is crucial for evaluating wood's fire behaviour and its response to different fire scenarios.

Timber joints, acting as crucial points of connection between wooden members, play a pivotal role in determining the overall stability and longevity of wooden structures [2]. However, due to timber's combustible nature, such structures are susceptible to fire. Merely focusing on a fire design approach for timber members alone proves insufficient if the joints cannot withstand the applied load during a fire incident. Hence, the design of connections, often the weakest points in timber construction, is likely to dictate the structure's overall fire stability. Despite recent endeavours to experimentally investigate and simulate the behaviour of timber connections under elevated temperatures, their thermal response remains incompletely understood. This complexity arises from the intricate nature of these connections.

Despite the widespread use of glued joints in modern timber construction, there remains a relative scarcity of literature regarding their performance characteristics. Current studies primarily concentrate on traditional mechanical fastening methods like nails and bolts, with limited attention devoted to understanding the behaviour and efficacy of glued connections. This gap is especially evident concerning fire stability and structural stability, where the performance of glued joints may diverge significantly from that of conventional mechanical connections.

This research seeks to address this significant gap by conducting a thorough examination of the performance of glued timber joints, specifically focusing on three prominent wood species: Beech, Spruce, and Pine. Through experimental testing, the study aims to shed light on the fire behaviour, fire stability, and failure mechanisms in timber connections. By employing advanced testing methodologies, such as cone calorimeter testing and stability analysis, this research endeavours to offer valuable insights into the behaviour of glued joints under various loading conditions and heat exposures.

1.1 Objectives

The following objectives define this thesis:

1. To investigate and analyse the fire behaviour of various timber joints compared to a control sample.
2. To examine how fire exposure affects the fire behaviour of different wood species.
3. To compare the fire behaviour and stability (joint failure) of identified joint types across different wood species, including beech (hardwood), pine, and spruce (softwood).
4. To determine the impact of joints on char formation, char properties, and thermal penetration depth in timber joints during burning, using bench-scale reaction to fire tests.
5. To compare the fire performance and failure characteristics of identified joints, considering variations in spruce wood thickness.

1.2 Scope

This thesis aims to understand the behaviour of joints across three different wood species. The research contributes two parts: understanding the behaviour of the joints in developing fire scenarios and understanding fire stability in fully developed fire scenarios. Experimental setups, including cone calorimeter tests and bench-scale reaction to fire tests, are utilized to comprehensively investigate the performance of glued timber joints under various conditions.

1.3 Limitations

Conducting full-scale experiments and standard fire tests is the ideal solution to understanding the actual behaviour of the jointed wood samples [4] [8]. Though small-scale tests provide valuable insights, they may not represent the behaviour in the jointed column and beam of any structure. Scaling up these results to larger structures could yield different results due to factors like increased heat accumulation and structural dynamics. However, due to the scope limitations of the project, cone calorimeter test has been conducted as it is most widely used bench-scale instruments to elucidate the reaction-to-fire properties [7]. Also, this study performed a small-scale test to analyse the failure of the joints.

The scope of the project is restricted to three types of wood (Pine, Spruce, and Beech) and five joint types due to the thesis duration. This limited scope may not capture the full range of possible wood and joint configurations used in construction, potentially overlooking important variations in fire behaviour.

The cone calorimeter tests used three different heat flux levels, but these may not fully mimic the complex fire conditions encountered in real-world scenarios. Factors like airflow, surrounding materials, and fire duration could influence fire behaviour differently than in controlled laboratory settings. The study primarily focused on thermal properties such as heat release and charring rate. While important, other factors like structural integrity, moisture content, and material aging could also affect the fire stability of jointed timber structures. But the selected properties are based on the scope of the work.

1.4 Methods

This section outlines the methodologies employed to investigate the fire behaviour and fire stability of timber joints. The methods discussed include a literature review and an experimental campaign. The literature review serves as the initial step to improve understanding of the concepts planned for experimental exploration in subsequent chapters. Additionally, previous studies on the fire stability of jointed wood and the implications of bench scale tests are reviewed. Following this, laboratory experiments are conducted. Finally, the data from the experiments are analysed to draw meaningful insights and conclusions.

1.4.1 Literature Review

A comprehensive literature search has been conducted to investigate the fire behaviour and fire stability of timber joints. The search has been carried out using two scientific databases, Scopus and Web of Science, as well as the search engine Google Scholar. Keywords such as ‘cone calorimeter’, ‘fire behaviour’, ‘fire resistance’, ‘wood behaviour’, ‘timber behaviour’, ‘heat exposure’, ‘joint behaviour’, and ‘glued joints’ have been employed to identify relevant studies.

The primary aim of the literature review has been to gain a thorough understanding of existing research and theories related to the fire behaviour of joints, with a particular focus on different types of wood. Additionally, the review has sought to investigate the fire stability of jointed wood and to examine previous bench-scale experiments concerning this behaviour. Key concepts, theories, available data, and methodologies used in previous studies have been identified during this process.

During the literature review, the focus has been placed on understanding fire behaviour. Initially, the search process has encountered some confusion due to variations in terminology and scope. To address this, the search has been systematically divided into categories focusing on different wood properties, the burning behaviour of wood, and studies that have conducted bench-scale tests. Some literature has also been provided by BAM, based on their previous work on wood, which has included a shared library listing various relevant papers. This structured approach has ensured comprehensive coverage of the relevant literature, providing a solid foundation for understanding the fire behaviour and stability of timber joints.

1.4.2 Experiments

To meet the identified goals, two main laboratory tests have been conducted: the cone calorimeter test and the stability test. The detailed methodology of these tests will be covered in Chapter 3. To achieve Objectives 1, 2, and 5, the cone calorimeter test has been conducted to evaluate the behaviour of jointed wood. To achieve Objectives 3, 4, and 5, the bench-scale fire stability test has been conducted to assess the fire stability of the wood. Objective 5 has been addressed in both tests, as it involves examining the impact of thickness variation.

Chapter 2 Literature Review

In this chapter, the literature on wood properties and its burning process is explored in section 2.1 and section 2.2, aiming to improve understanding of the concepts planned for experimental exploration in subsequent chapters. Additionally, previous studies on the fire stability of jointed wood and the implications of bench scale tests are discussed in section 2.3. The relevant contributions of other authors are duly acknowledged for their relevance to the aims and objectives of this thesis, thereby supporting the research presented in the following chapters.

2.1 Wood Properties

Wood is a remarkable natural composite material, comprising a mixture of polymers such as cellulose, hemicellulose, and lignin, which form long fibres [9] [10] . One can visualize timber as a collection of flexible straws bound together. When subjected to external forces, this assembly reacts differently based on several factors: the thickness of each straw (cell thickness), the adhesive material (lignin) that binds them, and the direction of applied force, which can be parallel or perpendicular to the grain of the wood. This property of wood, termed orthotropy, denotes its mechanical and thermal characteristics varying with grain direction. Typically, timber design considers two principal directions: parallel and perpendicular to the fibres [11].

Being a natural material, wood exhibits significant variability in properties not only across different species or geographical regions but even within the same tree. The inherent heterogeneity and unpredictability of wood pose challenges for structural design, often necessitating over-engineering to ensure safety. Furthermore, the distinct variations in the longitudinal lamellae, radially and tangentially, contribute to considerable variability in bond line performance [12]. In addition to its structural properties, the behaviour of wood in fire is influenced by its chemical composition, species, density, and moisture content [1]. These factors collectively shape its response to fire exposure.

The surface pH and acidity levels of wood vary between deciduous and coniferous species, as well as between hardwood and softwood. Even within a single species, different parts such as the heartwood and sapwood may exhibit differing pH levels. Hardwood primarily consists of vascular tubes, or pores, which facilitate water transportation within the wood. In terms of composition, hardwood typically contains approximately 40-50 wt.% cellulose, 15-25 wt.% lignin, and 15-35 wt.% hemicelluloses [13]. These pores contribute to the distinct grain pattern observed in hardwood, enhancing its density and workability.

Hardwood finds extensive application in the production of premium furniture, decking, flooring, and long-lasting constructions. Among hardwood varieties, beech wood stands out for its characteristics such as heaviness, hardness, strength, and remarkable stability to shock, making it a preferred choice for projects requiring durability [14]. Despite its favourable properties, beech wood undergoes significant shrinkage, necessitating careful drying processes to mitigate potential issues. Its smooth machinability, excellent turning capabilities, and stability to wear further enhance its appeal. Additionally, beech wood readily accepts preservative treatments, enhancing its longevity and versatility.

Softwood and hardwood share similar cellulose content, but softwood contains a higher proportion of lignin, typically ranging from 25 wt.% to 35 wt.%, along with approximately 20 wt.% hemicellulose [6]. Generally, softwood exhibits lower density and moisture resistance compared to hardwood, although there are exceptions. For instance, spruce, despite its susceptibility to debonding [15], is extensively used in structural applications and thus extensively tested, complicating direct comparisons. To explore this further, this study examines two different thicknesses of spruce wood. Density, influenced by porosity and species, tends to be lower in softwoods like spruce (400-500 kg/m^3), leading to lower thermal conductivity compared to hardwoods such as beech, ash, and oak (670-770 kg/m^3) [15]. Pine wood, another common softwood, varies in characteristics depending on the species. Some types of pine are moderately heavy, strong, hard, and stiff, with moderate shrinkage and high shock resistance [14]. Hence, for this study, beech, spruce, and pine were selected as representatives to investigate fire behaviour and stability.

2.2 Burning of Wood

Numerous studies have delved into the combustion processes of timber [1], [16], [17]. These investigations show that when exposed to heat, wood, as a mixture of natural polymers, breaks down mainly by releasing water, combustible, and non-combustible pyrolysis gases, and by forming a solid char residue. The thermal degradation of wood is intricately tied to temperature variations, a subject scrutinized by multiple researchers [1], [16]. Given that wood constitutes a composite material with diverse components, it boasts various layered cell structures, all of which contribute to its mechanical properties [9]. The decomposition of these components and cell structures occurs at distinct temperatures, further influencing the overall combustion process.

As wood undergoes heating, its ability to bear loads gradually diminishes. Even moderate temperatures, hovering around 65°C, can induce a lasting reduction in its mechanical properties. However, the impact on strength reduction due to heating varies significantly depending on experimental conditions. For instance, when subjected to different loading cases such as tension and compression, timber exhibits distinct declines in strength and elastic modulus, adding complexity to the structural analysis of heated timber components.

Heating timber above 100°C causes the evaporation of chemically unbound moisture trapped within. As temperatures rise further, chemical decomposition, known as pyrolysis, involves numerous interdependent reactions that can further degrade timber's load-bearing capacity [1]. It is typically assumed that combustible pyrolysis gases are produced, and a solid residue (char) is formed around 300°C. At higher temperatures, the char keeps undergoing smouldering and oxidation in the presence of enough oxygen [16].

The thermal disintegration of wood is commonly described as a series of distinct decomposition phases. There is ongoing discussion about the exact temperature limits of these phases, with certain researchers suggesting that timber loses all residual strength beyond a threshold as low as 200°C, while others indicate the 360°C isotherm as the position of the pyrolysis front [18]. This disparity may stem from the diverse components comprising timber, each with varying decomposition temperatures. Moreover, since these decomposition phases can overlap and lack clear delineation, defining the "onset of pyrolysis" may vary, introducing further discrepancies. Interpretations may be influenced by factors such as the quantity or concentration of measurable pyrolysis gases and the selected deviation from ambient conditions to define the beginning of pyrolysis.

Moreover, listing single temperature values can lead to ambiguity, as it's unclear whether they pertain to surface temperatures of timber samples (which are notoriously challenging to measure accurately) or temperatures at specific depths. The density (ρ), specific heat capacity

(cp), conductivity (k), and moisture content of timber have all been shown to influence temperature distribution within the material. These factors display significant variation not only among different timber species but also across environmental conditions.

Additionally, the method used to measure timber temperature can exert a significant influence. Factors such as thermocouple diameter, placement, and position can greatly affect the accuracy of temperature measurements at various depths. Together, these factors result in significant discrepancies in the critical temperatures identified for the various decomposition phases of heated timber.

Wood, being a dense charring substance, undergoes a complex process where char formation is primarily driven by the contributions of lignin and cellulose [19]. As noted by Lowden et al. [16], the initial peak in Heat Release Rate (HRR) corresponds to surface ignition. Subsequent combustion generates heat that sustains material pyrolysis, leading to the release of more volatile gases [20]. The decline in HRR is attributed to the development of a char layer, which acts as insulation, slowing down the pyrolysis process and impeding the transfer of heat and volatile gases within the material [21] [22]. The occurrence of a second or final peak is believed to result from material burn-through and char cracking, facilitating the release of additional volatile gases [23]. By a detailed understanding of why and when the second or concluding peak in heat release rate (HRR) occurs, insights into the burning behaviour of different wooden structures can be attained.

Tran et al. propose that the second or concluding peak arises due to an elevation in the bulk temperature of the remaining material coinciding with the pyrolysis zone reaching the rear side of the sample [24]. Research conducted by the Forest Products Laboratory [14] indicates that this peak is attributed to the pyrolysis zone extending to the sample's rear side, resulting in heightened temperature and HRR. The Forest Products Laboratory [14] investigated HRR under various heat flux intensities. Overall, these studies prove the influence of the rear side material of the wooden sample on the second peak behaviour.

In both academic studies and real-world scenarios, the progress of thermal decomposition in timber is frequently measured by the "charring rate" (mm/min). As mentioned earlier, this rate is closely linked to the location of the pyrolysis front within the timber, usually estimated by the 300°C isotherm—a value chosen somewhat arbitrarily within the temperature range favourable for timber's thermal breakdown.

The thermal decomposition and combustion processes in timber are complex and closely linked to the deterioration of its mechanical characteristics [25]. Once temperatures within the timber reach approximately 60°C, a gradual decline in its structural integrity begins, persisting until the timber returns to ambient conditions. This process encompasses the entire duration of a fire and subsequent structural cooling, illustrating the intricate relationship between thermal changes and mechanical properties in timber. Beyond 200°C, thermal decomposition results in the generation of both combustible and non-combustible pyrolysis gases, alongside the formation of a char layer [1], [10], [26], [25]. As elucidated earlier, the rate of char formation hinges on the pace of pyrolysis. Thus, any factors influencing timber combustion directly impact char production.

Furthermore, certain studies have explored the impact of the char layer on the behaviour of the second or concluding peak. Gan et al. [27] attribute the occurrence of the second peak to the formation of cracks in the char layer, facilitating an easier pathway for combustible gases within the wood. As these cracks expand, the peak heat release rate (PHRR) is achieved. The authors note that densified wood exhibits a lower and delayed PHRR compared to normal wood due to its char structure possessing thinner and shallower cracks. Das et al. [28], [29] support Gan et al.'s findings, emphasizing the significance of the char structure on HRR extent. They suggest that a dense and rigid char structure impedes mass and energy transport more than a cracked char structure.

Bartlett et al. [1] also investigated the impact of wood density on the charring rate, finding that higher density leads to a slower charring rate. They argue that higher density necessitates more energy for pyrolysis, thus slowing down the char formation process. Variations in fire behaviour have been noted among jointed wooden samples, attributed to differences in factors such as the char layer, wood properties, presence of cracks or openings, and adhesives. Therefore, this study aims to explore the variations in different wooden samples resulting from jointing and exposure to heat.

2.3 Fire Stability of Jointed Wood

Enhancing our understanding of how glue-laminated timber (GLT) behaves under fire exposure is crucial for advancing fire safety design. Typically, glulam beams undergo bending tests in standard fire resistance assessments [30]. However, it's widely acknowledged that large-scale standard fire tests for glulam beams are challenging—they are time-intensive, costly to set up, and may not fully capture the material's fire performance [31].

In the realm of timber joints, various tests have been conducted on common types such as finger joints and half-lap joints. However, comparative analyses among these tests are often elusive. For instance, Hirst et al. [32] delved into the structural behaviour of timber beams spliced with half-lap joints, employing wooden dowels in four-point bending tests. Their investigation, with the lapped surface oriented perpendicular to the applied load, revealed that the predominant failure mode of the spliced beam was cleavage fracture of the timber elements, rather than shear failure of the dowels. Song et al. [33] investigates the impact of service damage on the fire resistance and structural integrity of traditional timber mortise-tenon joints under static loading and fire exposure.

Similarly, studies focusing on the mechanical and structural performance of wood joints shed light on different aspects. Arciszewska-Kędzior et al. [34] scrutinized the mechanical performance of timber beams spliced with half-lap joints, utilizing wooden dowels and subjecting them to forces parallel to the lapped surface. Meanwhile, recognizing the inherent uncertainties in wood mechanical properties, Kunecký et al. [35]‘s research approach encompassed both experimental and numerical methods to explore the structural performance of spliced beams.

König et al. [36] investigated GLT beams featuring finger joints on the tension side exposed to fire. These finger joints were bonded using various structural adhesives, including melamine-urea-formaldehyde (MUF), phenol-resorcinol-formaldehyde (PRF), and polyurethane (PUR), all meeting current approval criteria for load-bearing timber components. At normal temperatures, the bending resistance among the beams showed no notable differences. However, in fire conditions, beams with PUR and MUF adhesives in the finger joints exhibited bending resistances only 70 to 80% of those with PRF-bonded finger joints. Polyurethane (PUR) adhesives, especially those used structurally, are thermosetting materials that exhibit significant changes at high temperatures [37]. Initially, they undergo thermal degradation with minor mass loss, followed by extensive thermal decomposition that alters their chemical structure and reduces mechanical properties. As the temperature rises and reaches the glass transition point, PUR transitions from rigid to flexible, impacting adhesion performance. Unlike thermoplastics, thermosetting PUR does not melt but degrades, maintaining structural integrity until substantial decomposition occurs [38].

Frangi et al. [39] conducted a series of tensile tests at elevated temperatures on finger joints bonded with five different adhesives, including four types of one-component polyurethane adhesives and one melamine-urea-formaldehyde adhesive. These tests demonstrated a significant reduction in strength for the finger joints as temperature increased. Moreover, distinct variations in strength reduction and failure were observed among the different adhesives. The relative strength reduction, particularly at 100°C, ranged from 50 to 85% of the strength observed at normal temperature (20°C). Notably, specimens bonded with three of the adhesives displayed a strength reduction exceeding what would be anticipated for timber in fire conditions. Thus, it is reasonable to anticipate that the adhesive's behaviour at elevated temperatures could significantly impact the load-bearing capacity of finger joints.

Besides Regueira et al. [40] evaluates the fire performance and load-bearing capacity of rounded dovetail timber connections, highlighting their inability to meet R30 fire resistance standards and the need for improved simulation methods to account for internal heating effects. In large-scale tests, the overall outcome is influenced by the dynamics of the structure, whereas the small scale becomes effective in terms of understanding material behaviour [31]. Consequently, from the literature it has been found that investigations have been conducted under bench-scale setups both for glued and mechanical joints. Despite variations in investigating parameters, experimental setups, and test procedures, they shared limitations in their work. The results were accompanied by visual observations. Overall, their work served as motivation for the development of this experimental setup based on the scope of this thesis study. Although previous studies have presented various small-scale tests on joints, none of them have compared the behaviour of jointed and non-jointed timber. Therefore, this study aims to focus on comparing fire stability among different wood types as well as five different glued joints.

Chapter 3 Materials and Methodology

An experimental methodology was developed to evaluate the fire behaviour and stability of wood joints. Five different types of wooden joints—no joint, butt joint, half lap joint, 3-finger joint, and 6-finger joint—were analysed and compared across three different wood types. Each sample underwent testing under varying heat fluxes in the cone test, while the loading and heat flux remained consistent for all samples in the fire stability test. Detailed temperature measurements were conducted to track temperature changes within the timber's depth. This data helped estimate the depth of heating and charring rates, providing insights into the failure mechanisms of the jointed wood.

3.1 Materials and Sample Preparation

The timber samples utilized were made from Estonian Pine, Spruce, and Beech woods, each measuring 24mm in thickness. Additionally, 42mm of Spruce wood samples, were utilized for testing purposes. The experiment examined five types of joints: no joint, butt joint, half lap joint, 3-finger joint, and 6-finger joint. Commercial adhesive “Ponal”, branded as PUR(Polyurethane)-LEIM and manufactured by a German-based company Henkel AG, was employed for joint preparation. This glue was tested according to DIN EN 14257 standards, demonstrating heat resistance exceeding 8 N/mm² according to WATT 91. The timber samples used in the experiment accurately represent those commonly found in construction products.

Large-scale standard fire tests for glulam timber are known to be both time-consuming and expensive to set up. In response, efforts have been made to introduce small-scale or bench-scale tests, drawing from insights presented in the literature review in Chapter 2, to investigate the performance of jointed wood. To achieve the specified objectives of understanding fire behaviour during fire development and fire stability in fully developed fires, timber specimens were prepared in two different dimensions.

For the Cone Calorimeter test, specimens were sized at 100 mm × 100 mm with two different thicknesses 24mm and 42mm respectively. For the Fire Stability test, the tested samples measured 160 mm × 100 mm, also with two different thicknesses. Figure 1 illustrates the dimension of the samples used in the tests. The purchased jointed samples have been carefully stored under standard temperature (23°C±2°C) and humidity conditions (50%±5%) in BAM laboratory as shown in Figure 2.

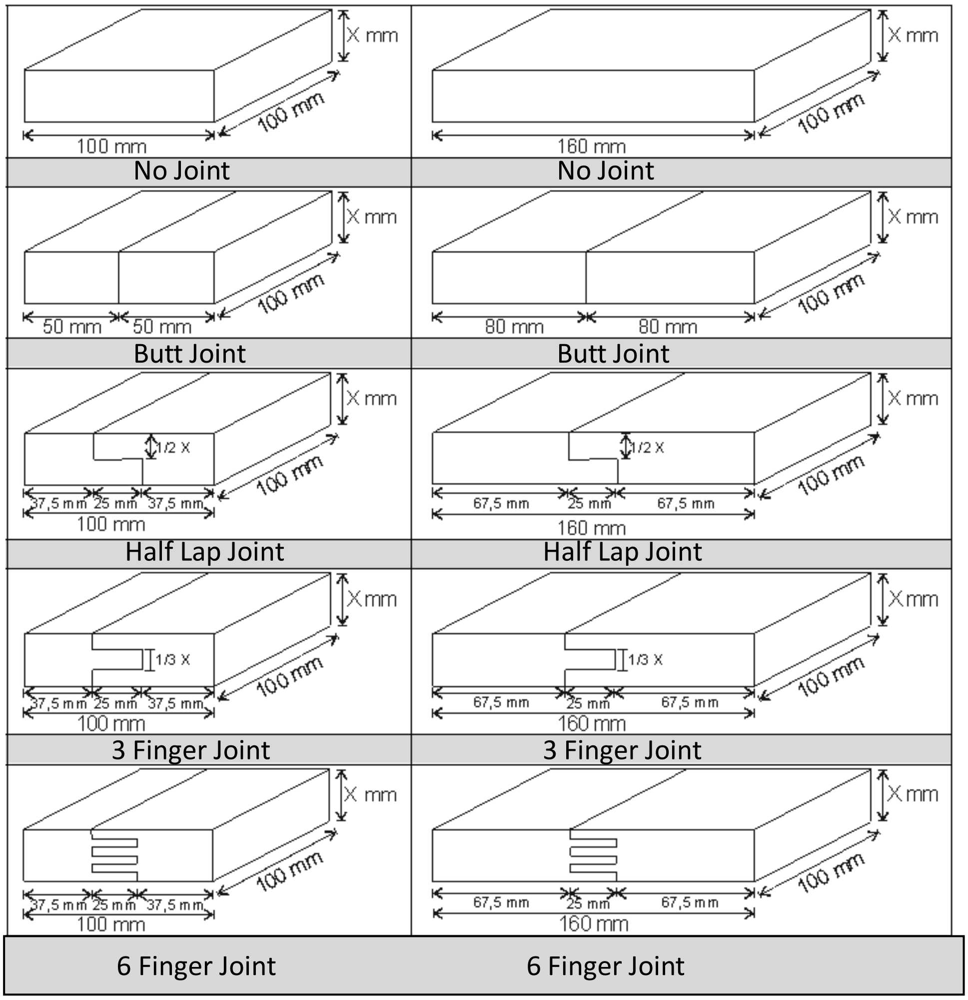


Figure 1: Dimensions of the Sample

Figure 2 : Samples Stored under conditioned temperature and humidity.

3.2 Test Setup

This research is structured around two main objectives. Firstly, it aims to investigate the behaviour of five different types of jointed wood across various wood species during the developing fire stage. Secondly, it focuses on understanding the stability of these jointed wood structures under fully developed fire conditions. To achieve these goals, two distinct tests were conducted: the cone calorimeter test and the Fire Stability test. By dividing the research focus into these two parts, the study aims to comprehensively examine the performance of jointed wood structures in different fire scenarios.

3.2.1 Cone Calorimeter Test

The cone calorimeter, renowned as one of the most widely utilized bench-scale instruments, serves to elucidate the reaction-to-fire properties of materials [7]. For this study, cone calorimeter by FTT Fire Testing Technology, UK experiments adhered to the standards outlined in ISO 5660-1 [41], utilizing equipment from the fire testing laboratory at Bundesanstalt für Materialforschung und -prüfung (BAM). The set-up of the cone calorimeter was chosen for its capability to simulate various fire scenarios through the manipulation of radiant heat flux impinging on the sample. Specifically, the radiant heat fluxes 35, 50, and 65 kW/m^2 was maintained averaging the temperature. The 35 and 50 kW/m^2 were proposed for this experiment as these were mentioned in ISO 5660-1, and 65 kW/m^2 was chosen to have a systematic row.

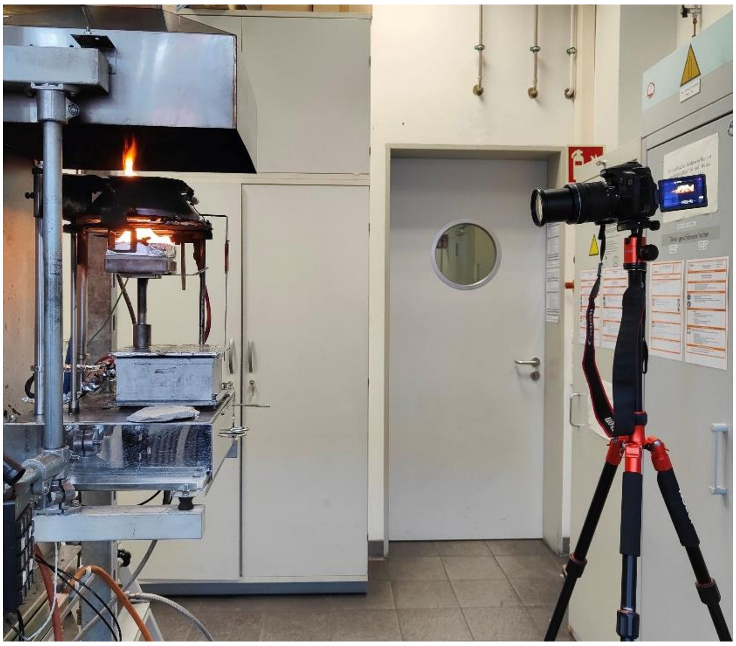


Figure 3 : Cone Calorimeter test set up.

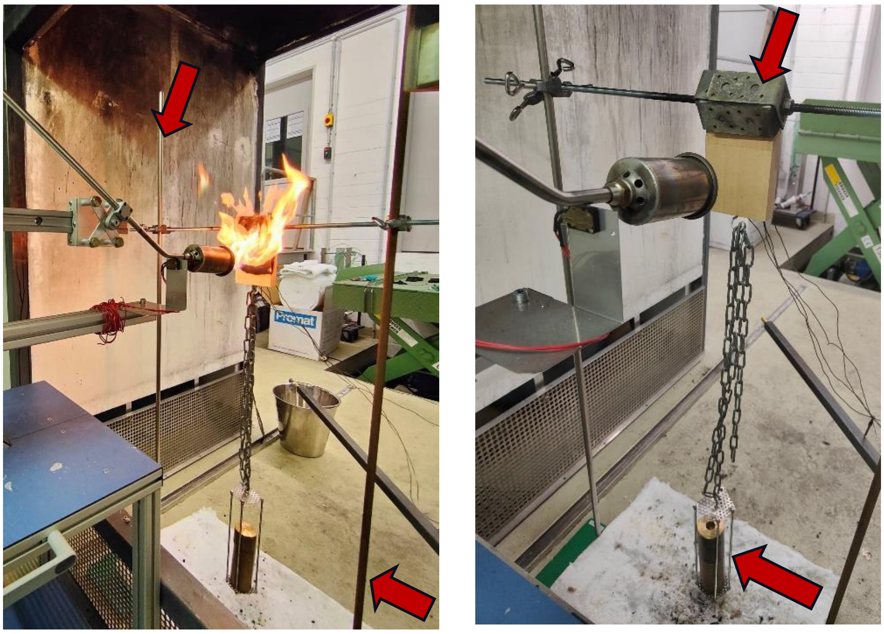
To achieve the desired heat fluxes, the coil temperature was carefully adjusted, while maintaining an exhaust duct flow rate of 24 l/s. Throughout each experiment, samples were positioned in a horizontal orientation, precisely 35 mm below the conical heater to provide enough space to the wooden sample to deform or react. A computer linked to the cone calorimeter was configured to record Heat Release Rate (HRR) data at 5-second intervals. This HRR data was derived from oxygen consumption measurements collected during the experiments. The time of ignition and failure time was measured manually.

3.2.2 Fire Stability Test

The fire stability was measured in a small-scale test which was developed to determine the resistance of the timber joints against a flame simulating a fully developed fire. This test was proposed to avoid the need for time-consuming and expensive large-scale tests typically used to measure fire stability [42]. The goal of this test was to determine the failure time of the jointed wooden sample. Therefore, the wooden samples were designed according to the specifications discussed in section 3.1, and the test setup for this test can be seen in Figure 4.

The test frame was constructed using two vertical stands as shown in Figure 6 (a) red arrows and a horizontal steel rod to hold the sample. The sample was clamped onto a stand and positioned to face a controlled burner flame. A metal cover shielded the top part of the sample from direct heat as shown in Figure 4 (a). Since the fire was aimed at heating the jointed part of the wood, before starting the test, the heat flux and flame temperature were adjusted for a specific distance between the burner and the sample surface, which remained consistent throughout. A total heat flux of 108±8 kW/m^2 was maintained at the sample surface. The distance between the burner and the sample was fixed at 14 cm, and the gas flow rate of the propane burner was kept constant at 3 L/min throughout the test.

Additionally, four K-type thermocouples were positioned just below the joints to measure the thermal penetration of the sample. Also, a 5 kg weight was attached to the lower half of the substrate as shown in Figure 4 (b). This 5kg weight was chosen based on experimental trials. The time taken for the jointed timber samples to fail when exposed to the burner flame was recorded to analyse the behaviour of different joints under heat exposure. In this research, the time of failure was considered to be when a large part of the wooden sample fell to the ground under its own weight.



(a) (b)

Figure 4: Fire Stability Test Set up.

3.3 Instrumentation

The cone calorimeter test was conducted in accordance with standardized procedures of ISO 5660-1 [41]. During the test, flammability parameters including ignition time and sustained flaming were recorded. Additionally, critical parameters such as Heat Release Rate (HRR), Total Heat Release (THR), and Mass Loss Rate (MLR) were characterized. These parameters serve as fundamental metrics for quantifying the fire performance of wood species and are essential for comprehending and potentially modifying wood behaviour in fire scenarios. The sample holder utilized for the test was an aluminium foil tray and ceramic wool was use below the Aluminium foil, and the test was conducted without a frame, as depicted in Figure 5.

Figure 5 : Sample Preparation for Cone Calorimeter Test

To prepare the sample for the fire stability test, specific modifications were made. Firstly, a 10 mm diameter hole was drilled horizontally in the width direction of the sample, as illustrated in Figure 6(a), to facilitate its secure placement in the test setup. Additionally, a 3.5 mm diameter hole was drilled in the middle of the surface at the bottom of the sample, as shown in Figure 6(b). This hole served the purpose of accommodating eye hooks, which were used to securely hold the weight during the test.

K-type thermocouples, each with a diameter of 1.5 mm, were inserted into the timber samples through pre-drilled holes, as detailed in section 3.2. The diameter of each hole matched that of the thermocouple end to ensure optimal contact and minimize air gaps. Figure 6(c) depicts the position of the drilled hole from the back side, while a schematic illustrating the precise positioning of the thermocouples can be found in the appendix I. Four thermocouples were positioned at various depths in same height within the wooden sample to track how heat spreads through it, as shown in Figure 7.

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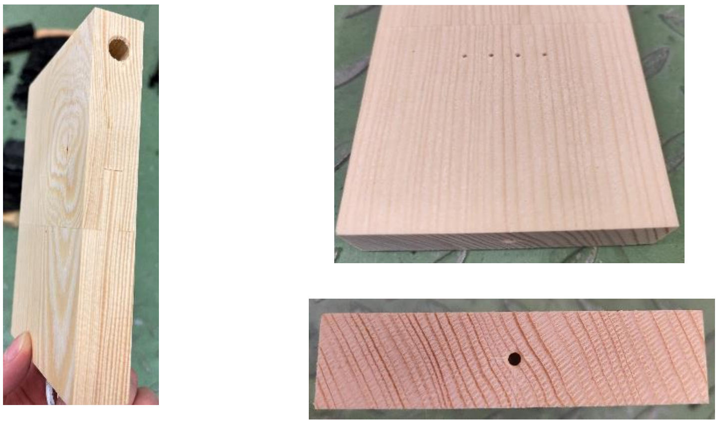


(a) (b) (c)

Figure 6 : Drilled hole for Fire Stability Test

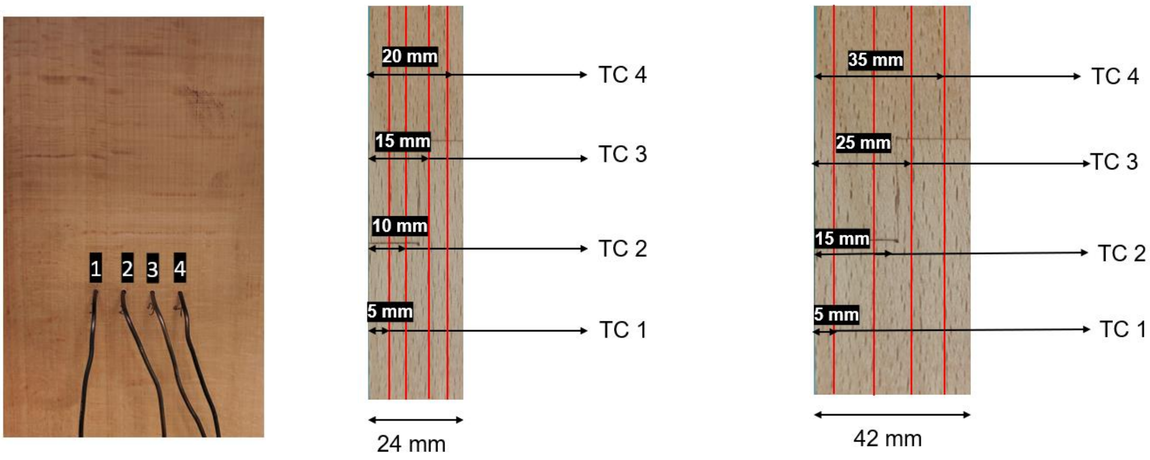


Figure 7 : Depth of the thermocouples

3.4 Testing Procedure

The thesis focused on two scenarios: fire behaviour during fire development and fire stability in fully developed fires. The experimental matrix for both tests is outlined in Table 1. The study utilized two types of wood: softwood (pine, spruce) and hardwood (beech), along with two different thicknesses (24 mm and 42 mm) of spruce wood. The testing procedures for both scenarios were distinct and will be elaborated upon in the following sections. In this research, a log book was used to track the test records, including the sample name and date. The weight of each sample was recorded before each test. During the test, visual changes in the sample were also documented.

Table 1: Experimental Matrix

Scenario	**Type of Wood – Thickness**	**Type of Joints***	**Heat Flux (kW/m^2)**	**No. Of Samples**	**Total No. of Samples**
Fire Behavior in Developing Fire	Pine -24mm	5	35, 50, 65	2	30
	Spruce-24mm	5	35, 50, 65	2	30
	Beech-24mm	5	35, 50, 65	2	30
	Spruce-42mm	5	50	2	10
Fire Stability in fully Developed Fire	Pine -24mm	5	108	3	15
	Spruce-24mm	5	108	3	15
	Beech-24mm	5	108	3	15
	Spruce-42mm	5	108	3	15
				Total	**160**

*No joint. Butt joint, Half-lap Joint, 3 Finger Joint, & 6 Finger Joint

3.4.1 Cone Calorimeter Test

Following the ISO 5660 standard, specimens were prepared according to specified dimensions and surface finish requirements. They were mounted on a sample holder to ensure consistent positioning during the test, with aluminium foil trays used to collect residue afterwards. An open metal frame was employed for the test setup.

Before conducting the test, the cone calorimeter and associated equipment such as gas flow meters, heat flux sensors, and temperature measurement devices were calibrated to ensure accurate readings. Three different heat flux levels (35, 50, & 65 kW/m^2) were tested as part of the thesis work. The prepared specimen was securely positioned in the cone calorimeter test chamber, ensuring centred alignment for uniform exposure to the heat source.

Initially, measurements were taken for 60 seconds without placing the sample. The test began with the placement of the samples. Considering the wood material's slower reaction to heat, the time to ignition was manually recorded. The test was stopped 5 minutes after flameout time. After each test, any residual combustion was extinguished with a water spray. One test and one repetition were carried out for each testing condition. The data collected during the test was analysed to evaluate the fire behaviour of the specimen, as discussed in Section 4 of the thesis.

3.4.2 Fire Stability Test

For this bench-scale test, the setup was arranged according to the scope outlined in section 3.2.2 of the thesis. Following this, calibration was performed as depicted in Figure 8. From this calibration, the heat flux and sample position were fixed. Two heat flux meters (One of the sensors was SBG-01, a combination of Gardon and Schmidt-Boelter and the Other sensor was Vatell TG1000, which is a Gardon-type sensor) were utilized for measuring heat fluxes, and an average value of 108±8 kWm^{-2} was established for the test.

A vertically oriented sample was positioned in the setup, with a propane burner used to directly heat the sample from the front. The test began with the ignition of the burner. It took approximately 30 seconds from ignition to stabilize the propane flow and achieve the desired heat flux. After this period, the burner position was adjusted to focus heat directly on the jointed part of the wooden sample.

Throughout the test, video recordings and pictures were captured from the sides. Observations included char falling off, buckling behaviour, and cracks and joint behaviour of the sample. The test continued until the wooden sample failed and broke into two pieces. Upon failure, the test was stopped, and the residual sample was extinguished with water. Broken parts of the wooden sample and residues were collected to observe their burning behaviour.

Figure 8 : Calibration for Fire Stability Test

Chapter 4 Result and Discussions

The following parts will cover both qualitative and quantitative observations regarding the fire behaviour of different types of jointed wood species. The result section has been divided into two main parts. The first section is dedicated to describing the fire behaviour in developing fire, while the second section focuses on fire stability in fully developed fire. Each main section is further subdivided into different parts.

The behaviour of the wooden sample in developing fire will be subjected to quantification through heat release rate analysis, along with the discussion of other parameters such as time of ignition, time of flameout, mass loss rate, total heat release, etc. Additionally, qualitative observations will be emphasized by comparing the burning process of the samples and the residues of the wooden sample. To assess the fire stability in fully developed fire, the failure time and the temperature profile of the wooden sample will be discussed. The charring rate and temperature during the failure of different wooden samples with and without joints will be compared. Qualitatively, visually observed failure behaviour, along with cracks and residues of the post-test samples, will be assessed.

4.1 Fire Behaviour in Developing Fire

To meet our predefined objectives 1, 2, and 5 from Chapter 1.1, this part is subdivided into three different sections. In the first section, the influence of different wood types on the behaviour of fire will be examined. Then, the performance of different joints on each type of wood will be compared, with consideration given to the variation in thickness for Spruce wood. Finally, in the last part, the variation in heat flux exposure will be compared for three different heat flux levels. In each part, the experimental results will be highlighted, with attention drawn to possible phenomena behind the reported observations. Moreover, after describing the results for every sample, the discussion of the results will be addressed.

4.1.1 Wood Species Influence

The first part of understanding the behaviour of the wooden sample involved examining the behaviour of two different types of wood (Hardwood and Softwood). Figure 9 depicts the heat release rate of various wood species under 50 kW/m^2, with Pine and Spruce representing softwood and Beech representing hardwood. The analysis of the heat release rate of the wooden sample was conducted using the cone calorimeter test, with the test procedure for these samples discussed in section 3.4.1. Wood is a thick charring material, with char formation primarily contributed by lignin and cellulose [1]. Figure 9 reveals that all wooden samples exhibit a two-peak behaviour in the heat release rate. While there are similarities in the behaviour observed in terms of both qualitative and quantitative data, differences have also been noted.

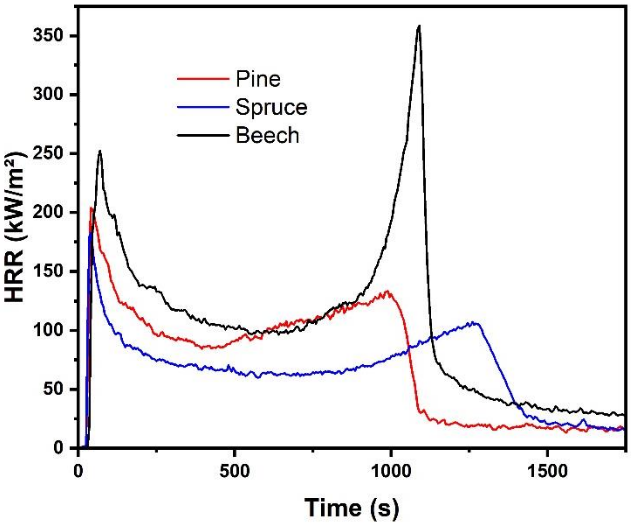


Figure 9 : The heat release rate (HRR) of different wood species under 50 kW/m^2

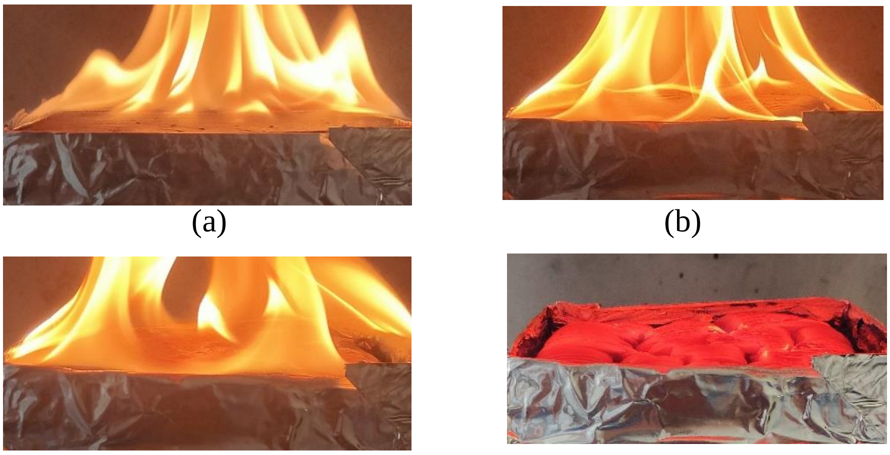
Figure 10 depicts the details of the Beechwood burning process at a heat flux of 50 kW/m^2. In Figure 10 (a), the beginning of the test reveals that Beechwood exhibits a longer ignition time, with the surface of the specimen nearly burning homogenously after 42 seconds. During this time, as observed in Figure 9, the heat release rate is lower than the first peak. Subsequently, in Figure 10 (b), flame spread occurs from the surface and lateral sides to the inner part. The first layer appears fully charred, providing surface protection and serving as an insulating effect, thereby slowing down pyrolysis. This leads to a gradual decrease in heat release rate around 495 seconds. At 1060 seconds in Figure 10 (c), the Beech sample starts wrapping, allowing the escape of additional volatile gases, resulting in an increase in heat release rate as seen in Figure 9. After that, in Figure 10 (d) around 1106 seconds, when the Beechwood is completely wrapped, it reaches the second peak in heat release. Towards the end of flaming combustion, the heat release rate begins to decrease, with the test continuing for 5 minutes after flameout.

(a) (b)

(c) (d)

Figure 10 : Burning of Beech Wood (a) Beginning of the test 42 sec, (b) 495 sec where the char layer formed in the upper layer, (c)1060 sec where the specimen started warping, (d) 1106 sec where specimen completely warped.

Figure 11 and Figure 12 describe the burning process of Pine wood and Spruce wood, respectively. In comparison with Figure 9, it is observed that in both cases, the ignition of the wood occurred at around the same time, indicating that both samples require the same pyrolysis time to burn. Subsequently, the first peak in HRR is typically a response to the ignition of the surface. Following the formation of the char layer, a slow decrease in HRR is observed. Finally, at the end of the test, the second peak is observed in both cases following the flameout of the wooden sample.

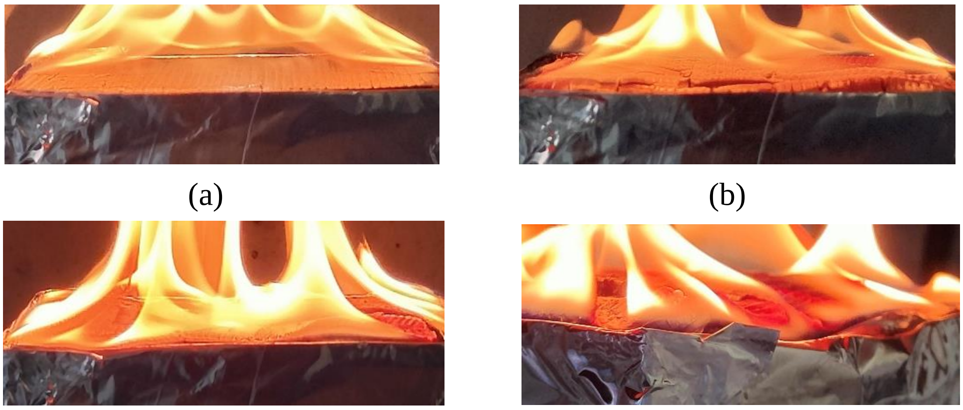


(a) (b)

(c) (d)

Figure 11 : Burning of Pine Wood (a) Beginning of the test 35 sec, (b) 500 sec where the char layer formed in the upper layer, (c)700 sec where the specimen shrunken from the sides, (d) 1000 sec where specimen completely burned.

By comparing the qualitative observations of Figures 11 and 12, it has been observed that Spruce wood required a longer time to burn, and the formation of cracks and deformation of the sample differed between the two cases. Although in both cases in (a) of the figures, the beginning of the test appeared quite similar and the char layer formed on the upper layer, in Figure 11 (c) after 700 seconds, the Pine wood started shrinking from the sides, and by 1000 seconds in Figure 11 (d), it had completely burned. Additionally, horizontal cracks were observed over the sample, and the sample shrank on all four sides. In Figure 12 (c), after 660 seconds, the Spruce wood started shrinking in the middle, but at the end of the test around 1200 seconds, there was still a good amount of residue present in the aluminium tray, and the Spruce wood did not shrink from the sides.



(a) (b)

(c) (d)

Figure 12 ; Burning of Spruce Wood (a) Beginning of the test 40 sec, (b) 300 sec where the char layer formed in the upper layer, (c) 660 sec where the specimen shrunken in the middle, (d) 1200 sec where specimen swelled in different parts.

Under 50 kW/m^2 heat flux, the burning behaviour of wooden samples exhibits similar patterns, including ignition, the first peak in heat release rate (HRR), a subsequent slow decrease in HRR, a second peak in HRR, and flameout. Though, there are differences observed both qualitatively and quantitatively among them. One of them is the effective heat of combustion (EHC) of different wooden jointed samples.

Figure 13 displays the comparison of effective heat of combustion (EHC) among different wood species, where the first and second peak heat release rates are compared for all the samples. The area of the first peak and second peak is determined based on the time of ignition and the time of flameout. The start and end times of each area under the first and second peaks are indicated in a separate table attached in appendix II. The effective heat of combustion (EHC) is determined by dividing the total heat released (THR) by the mass loss incurred during the test.

From Figure 13, it is evident that the EHC of the first peak area and the second peak area differs. The Effective Heat of Combustion represents the amount of heat released per mass unit during the combustion of the specified amount of fuel. Wood decomposes in subsequent step releasing different volatiles. The lower EHC observed during the first peak which dominated by the first decomposition steps, whereas the higher EHC during the second peak is attributed by the decomposition of the intermediate char.

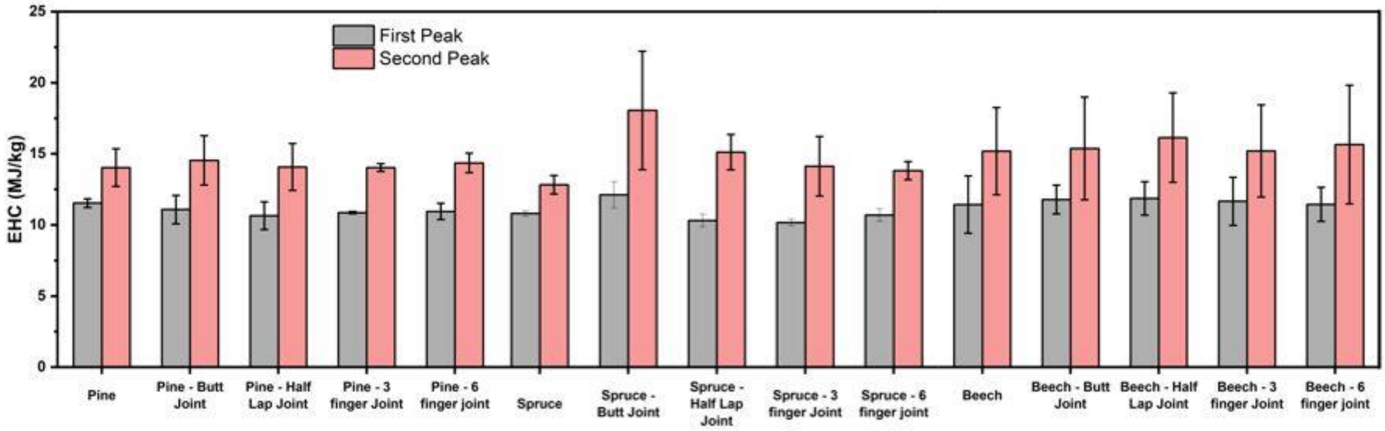


Figure 13 : The Effective Heat of Combustion (EHC) comparison of different wood species and joints (First and Second Peak) under 50 kW/m^2

Table 2 summarizes the fire properties of different wood species, namely Beech, Pine, and Spruce. A comparison reveals that the time of ignition and time to reach the first peak is earlier in Pine and Spruce wood compared to Beech. This suggests that softwoods (Pine and Spruce) are easier to ignite than hardwood (Beech) under the same heat flux due to the density difference [42]. Furthermore, Figure 14 demonstrates that the ignition time has a proportional relationship with density, where Beech has the highest density, and Pine and Spruce have the lowest density.

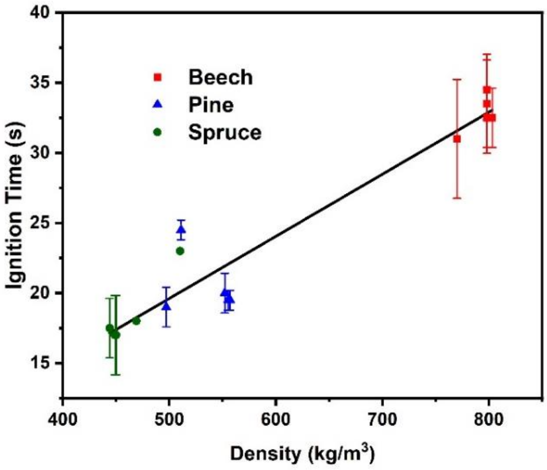


Figure 14 : The relationship between Ignition Time and Density

Table 2: The fire properties of different Wood.

	Beech	**Pine**	**Spruce**
Ignition Time (s)	32 ± 2	22 ± 1	23 ± 1
Flameout Time (s)	1192± 25	1140 ± 14	1387 ± 32
Flaming time (s)	1160 ± 27	1118 ± 15	1364 ± 32
Time to 1st Peak (s)	70 ± 1	42 ± 4	40 ± 1
First Peak HRR (kW/m^2)	292 ± 56	199 ± 7	192 ± 13
Time to 2nd Peak (s)	1118 ± 39	1015 ± 35	1273 ± 18
Second Peak HRR (kW/m^2)	328 ± 43	137 ± 5	106 ± 2
Average MLR (g/s)	0.130 ± 0.003	0.089 ± 0.003	0.071 ± 0.002
Initial Density (kg/m^3)	803 ± 6	511 ± 6	510 ± 3
Total HR (MJ/m^2)	174 ± 18	118 ± 2	108 ± 2

The flameout time for the wooden samples was difficult to choose by observation. So, by using carbon monoxide production graph the flameout time has set for all the sample using the same hypothesis. As it is evident that after flameout, the production of carbon monoxide increases rapidly due to the thermo-oxidation of char. Therefore, by comparing the curves of HRR and CO production, the flameout time for the samples is determined. Based on the ignition and flameout time, the Sustained flaming time of the sample is determined.

From the tabular data, it has been observed that the flaming time for Spruce wood is longer than for Beech and Pinewood. This is attributed to the consumption of the sample. As the flaming time has a reciprocal relationship with the consumption of HRR [6]. A significant difference has been found for time to first peak between hardwood and softwood. However, the time to reach the second peak is lower for both Pine and Beech than for Spruce. Additionally, for hardwood, it has been observed that the second peak heat release is higher than the first peak. Conversely, for softwood, the second peak is always found lower than the first peak. The average mass loss rate and total heat release are higher for hardwood than for softwood. A higher MLR indicates a higher pyrolysis rate with more heat released from their oxidation. The Average MLR for each species is shown in Table 1.

Overall, by comparing the HRR for all three types of wooden samples in Figure 9, it is observed that the first peak in HRR corresponds to the ignition of the surface, where the generated heat from combustion sustains pyrolysis, releasing more volatile gases. The decrease in HRR is attributed to the formation of a char layer, which acts as insulation, slowing down pyrolysis and impeding heat and volatile gas transport. The second/end peak is the result of material burn-through and char cracking, facilitating the escape of additional volatile gases. The final decrease in HRR occurs when no more volatiles are released, finishing flaming combustion and resulting in a steady baseline.

By analysing the burning process and observing the residue of Pine, Spruce, and Beech woods, it is found that the formation of cracks, char production, and the behaviour of wood samples differ under fire. When Beech wood started wrapping from the back, Spruce wood shrank only in the middle, and Pine wood shrank from all four sides. Figure 15 displays the residue of the three wooden samples from three different views: top view, side view, and rear side view. It has been observed that the residues are more fragile for Beech wood compared to Pine and Spruce wood. This residue also provides an indication of the burning of the sample. For Spruce wood, in the residue deeper cracks are observed, still a good amount of char layer initially protected the inner part. As the residue of the spruce is stronger than the Pine and Beech. This results a slow burning of the Spruce wood. Overall, different char deformation and cracking control the second peak HRR and thus resulting in relevant differences.

Top View

Side View

Rear Side View

(a) Beech (b) Pine (c) Spruce

Figure 15 : Top, Side and Rear Side view of the Residues of different wood

4.1.2 Joint Type Effects

In this part the different joints namely Butt joint, Half Lap Joint, 3 Finger Joint, and 6 finger joint is compared with no joint sample for Beech, Pine, and Spruce wood under 50 kW/m^2. For spruce wood 24 mm thickness and 42 mm thickness both will be analysed in this section.

Beech Wood

Figure 16 depicts the Heat Release Rate of different Jointed Beech wood under 50 kW/m^2 heat flux. From the graph, it is observed that all the samples started igniting at the same time and began to increase the HRR rapidly. Subsequently, as the surface of the sample burned, a char layer formed, and a slow decrease was observed. Following this, during the time for the second peak, material burn-through and char cracking facilitated the escape of additional volatile gases. Though, some differences were observed for different jointed wood.

It is noted from the Figure 16 that the second peak of the beech wood without joints is higher than other jointed beech wood, and the time to reach the second peak is lower than for the other jointed wood. This difference is attributed to the presence of the joint. Joints are connected with glue, and they hold the parts of the wooden sample. After a certain temperature, the glue line evaporates, and the wood sample starts to deform due to its burning behaviour. Thus, this combined effect of joint opening, cracks, and deformation of the sample enables changes in the second peak of the samples.

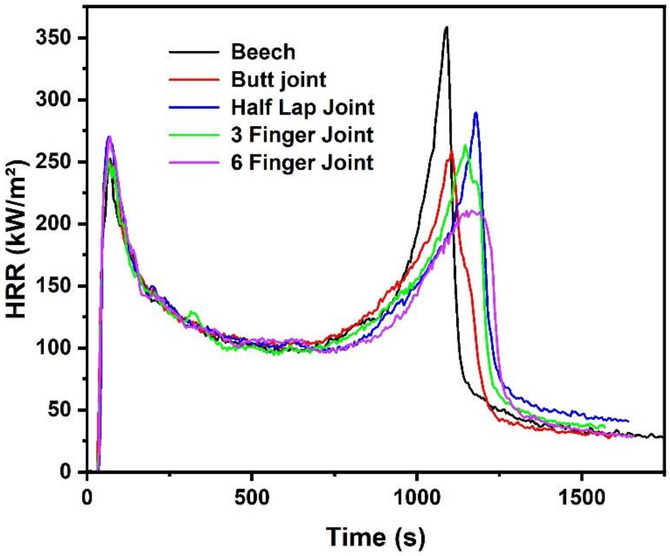


Figure 16 : The heat release rate (HRR) of different joints of Beech wood under 50 kW/m^2

Table 3 presents comparative data on different parameters of fire properties of Beechwood. It is observed that ignition time and time to reach the first peak are similar for all the samples, indicating similar initial burning behaviour due to the same surface area and wood type. Therefore, it is expected that the behaviour of the first peak will be the same for all samples. Regarding flameout time and total sustained flaming time, there are some differences, but considering the uncertainty, these differences are not significant. However, minor differences may be attributed due to the glue line. As the rear side of the wood participates in producing the HRR during the second peak area, and due to the combined effect of glue line opening and the deformation of jointed beech sample release of heat observed different.

Table 3: The fire properties of Beech Wood Joints

	Beech				
	No Joint	**Butt Joint**	**Half Lap Joint**	**3 Finger Joint**	**6 Finger Joint**
Ignition Time (s)	33 ± 2	31 ± 4	35 ± 2	34 ± 4	33 ± 2
Flameout Time (s)	1193 ± 25	1168 ± 18	1220 ± 7	1228 ± 25	1245 ± 7
Flaming time (s)	1160 ± 27	1137 ± 22	1186 ± 9	1194 ± 21	1213 ± 5
Time to 1st Peak (s)	70 ± 1	63 ± 4	65 ± 1	68 ± 4	65 ± 7
First Peak HRR (kW/m^2)	292 ± 56	287 ± 41	290 ± 28	288 ± 53	291 ± 28
Time to 2nd Peak (s)	1118 ± 39	1110 ± 7	1158 ± 32	1143 ± 4	1190 ± 35
Second Peak HRR (kW/m^2)	328 ± 43	298 ± 55	328 ± 54	271 ± 11	280 ± 9
Average MLR (g/s)	0.130 ± 0.003	0.128 ± 0.002	0.127 ± 0.004	0.127 ± 0.004	0.123 ± 0.003
Initial Density (kg/m^3)	803 ± 6	770 ± 1	798 ± 25	798 ± 17	798 ± 24
Total HR (MJ/m^2)	174 ± 18	171 ± 14	184 ± 27	179 ± 20	177± 17

Typically, for Beechwood, a complete deformation occurs during burning. In fact, in butt joint samples, the glue line decomposes after passing half of the time, causing both parts to behave as identical samples, and resulting in observed deformation for both parts of the sample. This phenomenon leads to faster flameout of the butt joint compared to others. Conversely, for other joints, the glue lines connect the parts of the wood, but as the line is not as straight as the butt joint, it takes some minor additional time to deform the samples. Overall, differences in the flaming time of the sample are noted. Yet there is no difference has been found in the ignition time, first peak HRR, average MLR, total HR, but in terms of the time to reach second peak HRR and the second peak HRR is found different due to the joint effects. As, this joint opens up the cracks in the char layer differently, which creating an easy pathway for combustible gases inside the sample [27]. Overall, joints allowing the cracks grow differently which results different second peak HRR, and time to reach second peak.

Pine Wood

Figure 17 depicts the heat release rate of Pinewood joints under 50 kW/m^2. The behaviour of Pinewood with different joints showed similar patterns in terms of the HRR graph. Although the ignition time and first peak behaviour are the same for all the samples, similar to Beechwood, differences are observed in the second peak.

As mentioned previously, the second HRR is similar for all samples as it is mostly dominated by the materials, but there are differences in the time to reach the second peak heat release. Samples with butt joints and no joints took a lower time than the other three joints. The reason is similar to Beechwood joints, as both Pine and Beech samples were observed to shrink and deform. Thus, the glue joints somehow connect the parts of the wood, leading to some minor additional time required for deformation. This characteristic of the wood joints significantly influences the values.

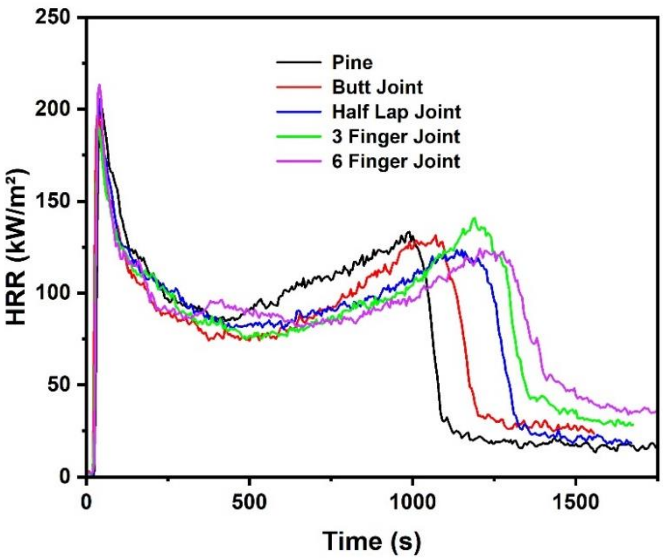


Figure 17 : The heat release rate (HRR) of different joints of Pine Wood under 50 kW/m^2

Although some similarities are found between Pine and Beech wood, in terms of second peak heat release, there are differences. In Beech wood without joints, the second peak heat release was higher, but in Pine wood, all the wooden samples with and without joints show similar second peak HRR. The second/end peak is an effect of the pyrolysis zone reaching the samples rear side, which increases both temperature and HRR [14]. When the pyrolysis zone reached the rear side of the sample, both pine and beech wood react differently in increasing temperature. Thus, results this difference in both wooden behaviours.

However, table 4 presents the fire properties of Pine wood joints to compare the differences and similarities quantitatively. From this tabular data, it is evident that there is no significant difference in terms of ignition time, time to first peak, first peak HRR, and average mass loss rate. However, there are some differences observed in flameout time, time to reach the second peak, and second peak HRR. After considering the repeatability, although these differences become minor, it is still interesting to note that joints have an impact on the behaviour of the second peak heat release rate.

Table 4: The fire properties of Pine Wood of different Joints.

	Pine				
	No Joint	**Butt Joint**	**Half Lap Joint**	**3 Finger Joint**	**6 Finger Joint**
Ignition Time (s)	22 ± 1	19 ± 1	20 ± 1	20 ± 1	20 ± 1
Flameout Time (s)	1140 ± 14	1163 ± 11	1260 ± 7	1265 ± 7	1300 ± 28
Flaming time (s)	1118 ± 15	1144±12	1241±6	1246±8	1280±27
Time to 1st Peak (s)	43 ± 4	35±0	38±4	38±4	38±4
First Peak HRR (kW/m^2)	199 ± 7	209±13	204±2	187±6	205±12
Time to 2nd Peak (s)	1015 ± 35	1068±4	1128±11	1160±42	1208±4
Second Peak HRR (kW/m^2)	137 ± 5	136±7	125±2	140±1	127±5
Average MLR (g/s)	0.089 ± 0.003	0.084±0.002	0.087±0.001	0.085±0.002	0.082±0.000
Initial Density (kg/m^3)	511 ± 6	497±4	557±16	555±3	552±15
Total HR (MJ/m^2)	118 ± 2	117±4	131±5	126±1	128±3

Overall, it was interesting to note that, despite Pine and Beech being two different types of wood, there are still some similarities in terms of the behaviour of wood joints. In both cases, the no joint and butt joint take a shorter time to reach the second peak heat release, whereas the other joints take longer. However, differences have also been observed in terms of the quantitative data. In this sense, both types of wood have different values, considering the differences in density, weight of the sample, as well as the presence of cracks and the release of volatile gases.

Spruce Wood

Figure 18 illustrates the HRR of different joints of Spruce Wood under 50 kW/m^2. It is surprising to note that the HRR of Spruce wood with and without joints showed similar HRR for both the first and second peak HRR. Char structure is important for HRR, a dense and rigid char hinders the mass and energy transport [27]. Due to the dense and rigid char of the spruce wood the joints do not create any difference in the char formation or creating pathway for combustible gases. Overall, due to this char behaviour no difference has been observed in among Spruce wood joints.

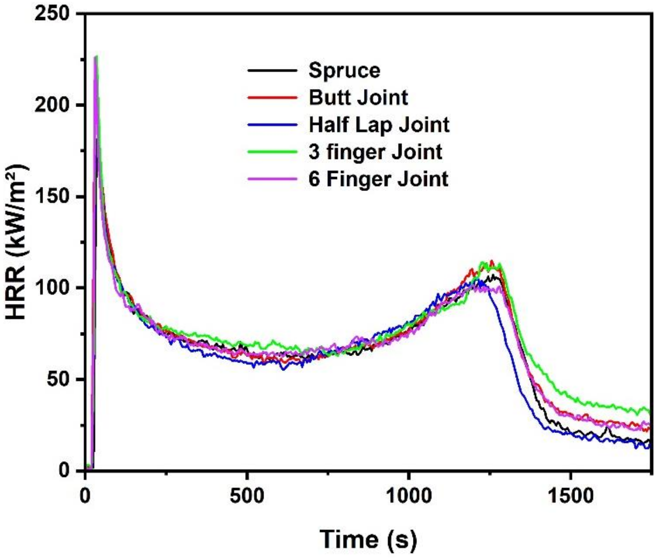


Figure 18: The heat release rate (HRR) of different joints of Spruce Wood under 50 kW/m^2

In the previous part, similarities and differences were observed for Beech and Pine wood, but in terms of Spruce wood, there are no differences. This again proves that joints influence the behaviour of fire when the joints are participating in changing the surface of the sample by opening cracks or holding the parts of the wooden piece. Previously, for Pine and Beech wood, shrinking or deformation in the second peak was observed, but for Spruce wood, there are no significant differences observed due to the joints. Some cracks were visible on the surfaces, which is a similar case for all of them, so there are not such differences due to the joints in the Spruce wood because of the dense char of the spruce wood.

Table 5 displays the fire properties data of Spruce wood for comparative analysis. From the data, it has been observed that all the parameters for Spruce wood, including the ignition time, flame out time, time to reach the first and second peak, the first and second peak heat release rate, as well as the MLR and THR, show similar results in the case of Spruce wood, considering the uncertainty. Since the density and weight of the Spruce wood were similar, there is no significant difference in the first peak. Additionally, the joint does not have a dominant effect on the second peak behaviour of Spruce wood.

Table 5: The fire properties of Spruce Wood Joints

	Spruce 24 mm				
	No Joint	**Butt Joint**	**Half Lap Joint**	**3 Finger Joint**	**6 Finger Joint**
Ignition Time (s)	23 ± 1	18±0	17±3	18±2	17±3
Flameout Time (s)	1388 ± 32	1378±18	1353±11	1368±18	1353±46
Flaming time (s)	1365 ± 32	1360±18	1336±13	1350±16	1336±43
Time to 1st Peak (s)	40 ± 1	33±4	33±4	33±4	30±4
First Peak HRR (kW/m^2)	192 ± 13	220±2	207±11	219±11	222±6
Time to 2nd Peak (s)	1273 ± 18	1265±14	1230±35	1215±14	1193±11
Second Peak HRR (kW/m^2)	106 ± 2	111±5	96±15	108±9	103±2
Average MLR (g/s)	0.071 ± 0.002	0.066±0.000	0.065±0.003	0.064±0.001	0.065±0.002
Initial Density (kg/m^3)	510 ± 3	469±2	449±13	444±9	450±2
Total HR (MJ/m^2)	108 ± 2	108±1	100±4	108±5	106±2

The fire behaviour under 50 kW/m^2 has been analysed for 5 different types of jointed Beech, Pine, and Spruce wood. Now, another thickness variation of Spruce wood, 42 mm, will be discussed. Figure 19 displays the HRR of different joints of Spruce 42 mm Wood under 50 kW/m^2, and Table 6 presents the quantitative data for this variable difference.

In Figure 19 Spruce 42 mm wood with different joints showed similar behaviour in terms of the HRR graph except for the but joint. It is observed that in the butt joint, the flaming time is shorter than the other joints. The probable reason for this is the weight of the sample, coincidently the weight for both test samples of the but joint had less weight than the other types of joints. In weight of the unburned sample was 169±13 g, whereas the no-joint sample weight was 210±1 g. But overall, for all the jointed wood the fire behaviour is similar just like the 24 mm sample. So, it is observed that this fire behaviour is identical for spruce wood, and the joint does not impact the fire behaviour of Spruce wood except from the total time of burning.

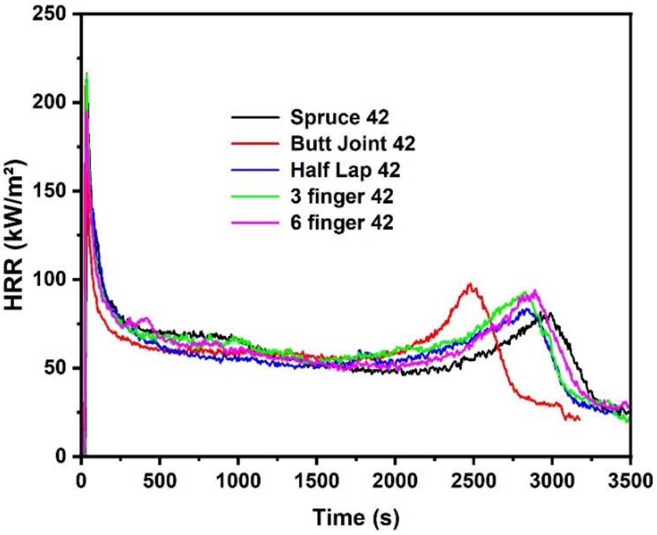


Figure 19 : The heat release rate (HRR) of different joints of Spruce 42 mm Wood under 50 kW/m^2

Table 6 presents information regarding the fire properties of 42 mm Spruce wood. Though there are no significant differences among the joints except for the butt joint. Moreover, differences are observed due to the thickness difference in the qualitative data. Specifically, the total burning time is longer in the 42 mm thickness compared to the 24 mm thickness. The initial peak heat release and time to reach the first peak are the same for both cases, as this phenomenon is dominated by the surface of the sample. However, differences are observed in the second peak heat release rate. The second peak of the 42 mm thickness is lower than the 24mm, which means with the increase of thickness, the release of volatile gases becomes less. Besides this, other parameters average MLR, Total Heat Release showed differences.

Table 6: The fire properties of Spruce 42 mm Wood Joints.

	Spruce 42 mm				
	No Joint	**Butt Joint**	**Half Lap Joint**	**3 Finger Joint**	**6 Finger Joint**
Ignition Time (s)	23±2	14±2	18±3	18±4	19±4
Flameout Time (s)	3145±120	2713±88	3030±7	3050±120	3093±18
Flaming time (s)	3123±118	2699±91	3012±10	3032±124	3074±14
Time to 1st Peak (s)	38±4	28±4	33±4	33±4	35±0
First Peak HRR (kW/m^2)	198±8	206±10	204±17	206±14	210±20
Time to 2nd Peak (s)	2920±99	2508±39	2858±32	2825±7	2868±32
Second Peak HRR (kW/m^2)	87±8	86±16	94±14	87±8	94±0
Average MLR (g/s)	0.057±0.002	0.051±0.001	0.057±0.000	0.053±0.004	0.052±0.002
Initial Density (kg/m^3)	517±3	403±30	504±3	476±19	466±21
Total HR (MJ/m^2)	195±11	162±14	196±5	192±13	195±7

Overall, for the wood with joints, the main difference is observed in the second peak. Though the second peak heat release is somehow similar, the time to reach the second peak is significantly different. This difference is found in Pine and Beechwood, whereas for Spruce wood, it was similar time for all the samples. For Beech and Pinewood, the joint introduced different char cracking and attempted to hold the sample together, which creates a difference from their actual behaviour. The residue of the burned wooden sample shows the cracks and the surface of the samples after burning. All the residue sample pictures have been shared in Appendix III.

For Spruce wood, by comparing different thicknesses, it is found that the burning of the 42 mm sample took longer time than the other, which is somewhat obvious as the greater thickness will take longer time. However, the behaviour of the HRR is similar for both thicknesses. But it would also be interesting to observe this phenomenon for the other two types of wood as well.

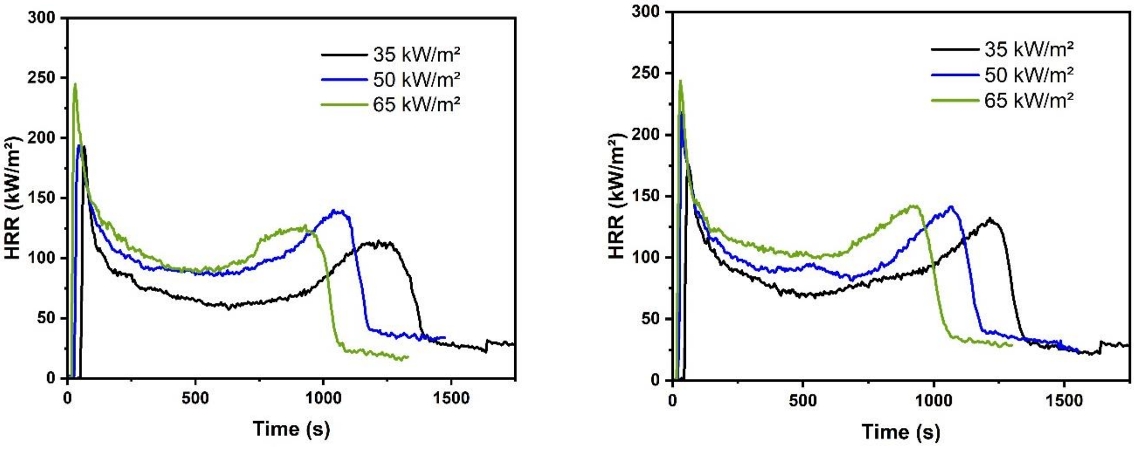
4.1.3 Heat Exposure Variation

In this section, heat exposure variation for different wooden samples and the behaviour of joints for 3 different heat fluxes have been observed. The heat fluxes 35, 50, and 65 kW/m^2 are compared for different jointed wood. In the following, only the behaviour of the 24 mm wooden samples is presented.

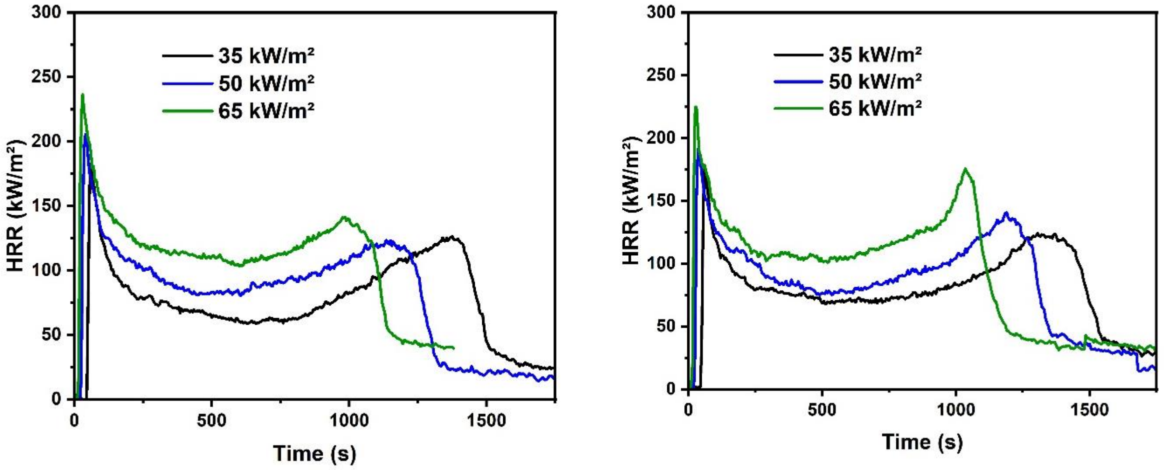
Pine Wood

Figure 20 depicts the heat release rate of different joints of Pinewood under 3 different heat fluxes, where (a) No joints, (b) Butt joint, (c) half lap joint, (d) 3 finger joint, and (e) 6 finger joint. For all the jointed wood under 3 different heat fluxes, the heat release rate exhibits two peaks. At first glance, it is evident that the heat flux of 65 kW/m^2 results in faster burning, while 35 kW/m^2 requires more time to burn. The burning behaviour of the wooden sample for different joints under 50 kW/m^2 was discussed in the previous section. The fire behaviour of the other two heat fluxes is compared here with 50 kW/m^2.

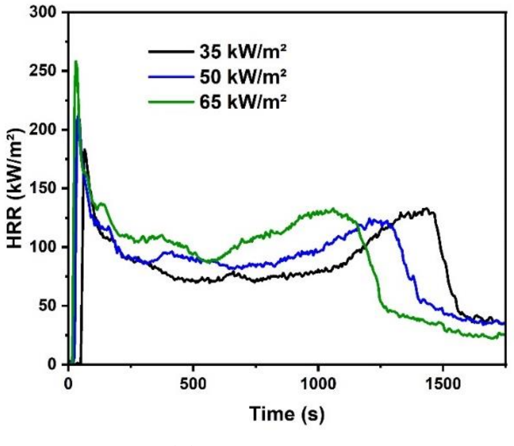
The similarity in the pattern of heat release rates (HRR) across different joints has been observed, albeit with notable differences in quantitation data. Table 7 presents the fire properties of Pinewood at 35 and 65 kW/m^2, while previous discussion in Table 4 focused on properties under 50 kW/m^2. A comparison of parameters across various heat fluxes reveals that at 65 kW/m^2, the initial peak heat release rate is substantially higher compared to the other two fluxes, although no significant difference is noted in the second peak heat release rate. It can also be said that the increase in heat flux contributes to the initial peak heat release, while over time, the formation of a char layer occurs, which occurs an insulating effect that slows down pyrolysis. Consequently, near the second peak, there is no significant difference observed in the second peak heat release rate but in terms of time to reach second peak the differences are noticeable. As, the total heat release is same but the heat exposure differences affecting the ignition time, and the total burning time as observed in Table 7. Overall, the heat release is observed higher for high heat flxes. Also, the crack formation over the residue of the burning wood is same under different heat exposure, Figure 21 (a) shows the residue of Pine wood under 35 kW/m^2 and in Annex III the residue of the Pine wood under 50 kW/m^2 have shown. So, this provides an indication that, due to the heat exposure variation the joints opening, and cracks formation doesn’t vary for jointed pine wood samples.



(a) No Joint (b) Butt Joint



(c) Half Lap Joint (d) 3 Finger Joint



(e) 6 Finger Joint

Figure 20 : HRR of Pine wood exposed to different heat fluxes (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint

Table 7: Fire behaviour properties of Pine Wood in different heat fluxes.

	Pine									
	No Joint		**Butt Joint**		**Half Lap Joint**		**3 Finger Joint**		**6 Finger Joint**	
	35	**65**	**35**	**65**	**35**	**65**	**35**	**65**	**35**	**65**
Ignition Time (s)	48±2	13±1	40±3	12±2	45±3	11±1	49±7	11±1	46±4	13±1
Flameout Time (s)	1345±7	1043±18	1328±46	998±4	1453±11	1123±39	1443±39	1143±32	1435±49	1140±90
Flaming time (s)	1298±5	1030±18	1288±49	986±6	1408±13	1112±40	1394±46	1132±31	1390±46	1128±98
Time to 1st Peak(s)	65±1	30±1	58±4	28±4	63±4	28±4	68±11	30±1	63±4	30±1
First Peak HRR (kW/m^2)	181±18	237±11	173±5	251±10	183±1	233±6	185±12	240±21	171±17	243±22
Time to 2nd Peak (s)	1185±42	940±14	1220±7	928±11	1350±35	1013±39	1328±32	1028±11	1373±88	988±95
Second Peak HRR (kW/m^2)	120±10	126±3	130±3	141±1	136±14	147±8	131±10	158±25	129±6	131±1
Average MLR (g/s)	0.073± 0.001	0.093± 0.001	0.074± 0.002	0.102± 0.008	0.078± 0.004	0.102± 0.010	0.076± 0.006	0.095± 0.004	0.076± 0.001	0.051± 0.058
Initial Density (kg/m^3)	493±5	496±8	494±1	501±7	569±13	551±6	558±29	553±13	562±15	558±6
Total HR (MJ/m^2)	111±4	113±2	113±4	116±1	127±6	127±11	130±4	135±2	129±4	120±7

Spruce Wood

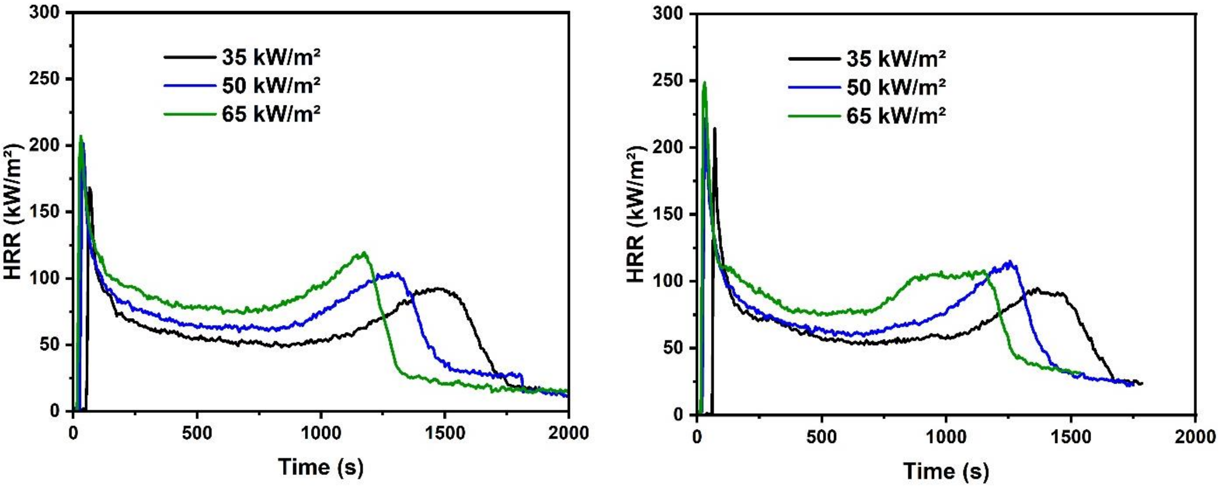
Figure 22 depicts the varied heat exposure effects on jointed spruce wood. It is observed from the figure that higher heat fluxes lead to faster ignition times. Overall, the fire behaviour remains similar across all samples, with each exhibiting two peak heat releases. However, in butt joint Figure 22 (b), the second peak heat release behaves differently at 65 and 35 kW/m^2; in both cases, the second peak persists for a longer duration. This phenomenon occurs because, upon separation from the glue line, one half of the sample begins burning, followed by the other half after some time, resulting in a shorter peak heat release but prolonged peak duration. Though this is not a common case for all the tested sample.

Additionally, the samples demonstrate quantitative performance variations under different heat fluxes. Table 8 presents the fire behaviour properties of Spruce Wood at 35 and 65 kW/m^2, while Table 5 previously outlined the properties of wood under 50 kW/m^2. By comparing the data for 3 different heat fluxes, it has been seen that, in terms of the parameter like time of ignition, following that time to reach first peak, flameout time there is differences due to the different heat exposure. In pine wood, in the first peak HRR was higher in 65 kW/m^2, but in spruce considering the uncertainty it is evident that, there is no significant difference found both for first and second peak heat release rate. But in the time to reach second heat release rate the difference is significant. Also, the crack formation over the residue of the burning wood is same under different heat exposure, for instance the Figure 21 (b) shows the residue of Spruce wood under 35 kW/m^2.

(a) Pine

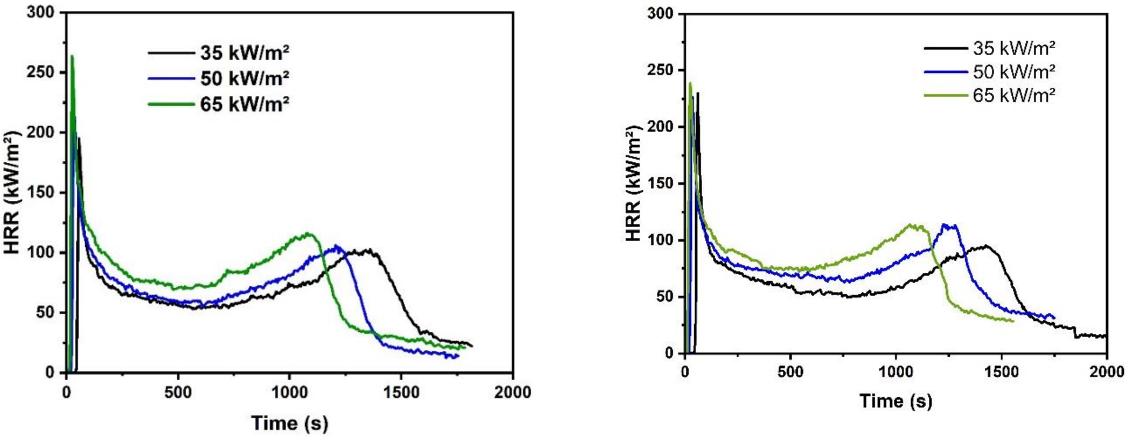
(b) Spruce

Figure 21 : Residues of the burned soft wood under 35 kW/m^2 (a) Pine, (b) Spruce



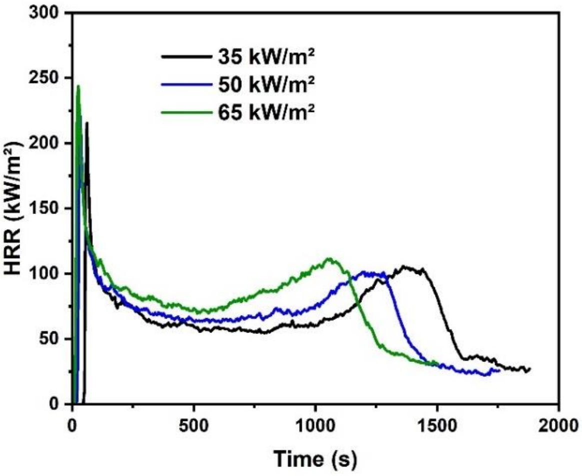
(a) No Joint

(b) Butt Joint



(c) Half Lap Joint

(d) 3 Finger Joint



(e) 6 Finger Joint

Figure 22 : HRR of Spruce wood exposed to different heat fluxes (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint

Table 8: Fire behaviour properties of Spruce Wood in different heat fluxes.

	Spruce									
	No Joint		**Butt Joint**		**Half Lap Joint**		**3 Finger Joint**		**6 Finger Joint**	
	35	**65**	**35**	**65**	**35**	**65**	**35**	**65**	**35**	**65**
Ignition Time (s)	51±1	13±1	50±10	12±1	43±1	11±2	42±5	11±1	43±5	10±1
Flameout Time (s)	1560±57	1243±11	1510±7	1218±4	1445±21	1143±18	1460±49	1153±18	1508±18	1165±21
Flaming time (s)	1510±57	1230±3	1460±17	1206±2	1402±23	1132±1	1419±45	1142±3	1465±23	1156±7
Time to 1st Peak(s)	65±1	28±4	65±7	28±4	58±4	25±1	55±7	25±1	58±4	25±1
First Peak HRR (kW/m^2)	164±6	210±4	199±21	244±7	193±3	249±21	213±25	243±5	213±5	243±1
Time to 2nd Peak (s)	1440±28	1170±7	1408±60	1135±21	1368±11	1043±53	1395±42	1058±11	1395±49	1070±28
Second Peak HRR (kW/m^2)	101±11	115±6	100±6	112±5	104±1	116±0	101±7	119±7	105±2	115±5
Average MLR (g/s)	0.062±0.002	0.083±0.008	0.060±0.001	0.079±0.007	0.059±0.000	0.081±0.005	0.058±0.003	0.080±0.003	0.058±0.001	0.074±0.001
Initial Density (kg/m^3)	503±4	501±10	480±2	473±4	446±4	453±1	440±0	452±8	460±6	451±16
Total HR (MJ/m^2)	103±0	111±3	106±5	114±2	103±1	107±1	103±2	109±3	106±0	109±7

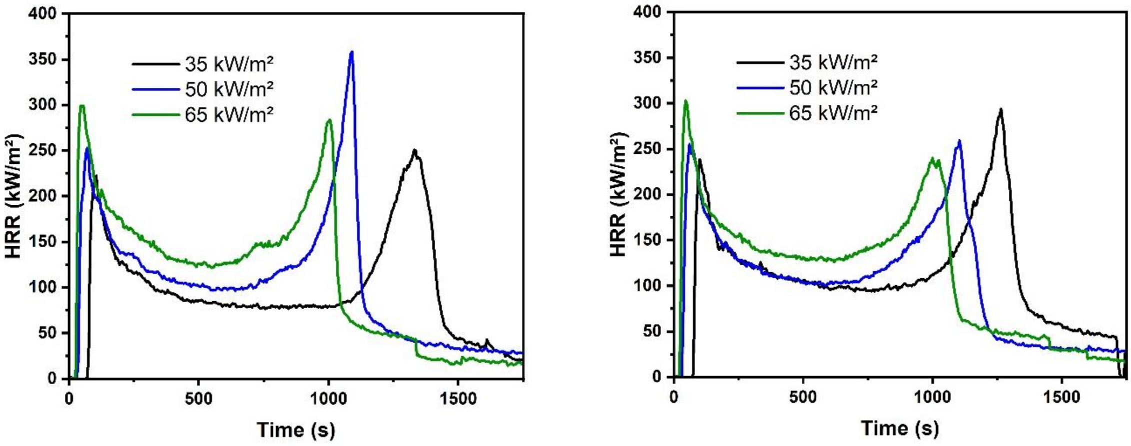
Beech Wood

In Figure 23, the residue of the burned sample under 35 kW/m^2 heat flux is displayed. Regarding crack formation or deformation of the wooden sample, no significant differences are observed in the residue compared to other heat exposure. Thus, the burning behaviour described in section 4.1.2 is applicable to all samples irrespective of heat exposure. Figure 24 presents the heat exposure effects on Beech wood under various heat fluxes. However, upon comparing tabular data and Figure 24, a significant difference is noted in the second peak heat release rate. The second peak HRR does not follow a consistent pattern as observed previously; in Beech wood, different joints exhibit varying Peak Heat Release Rates.

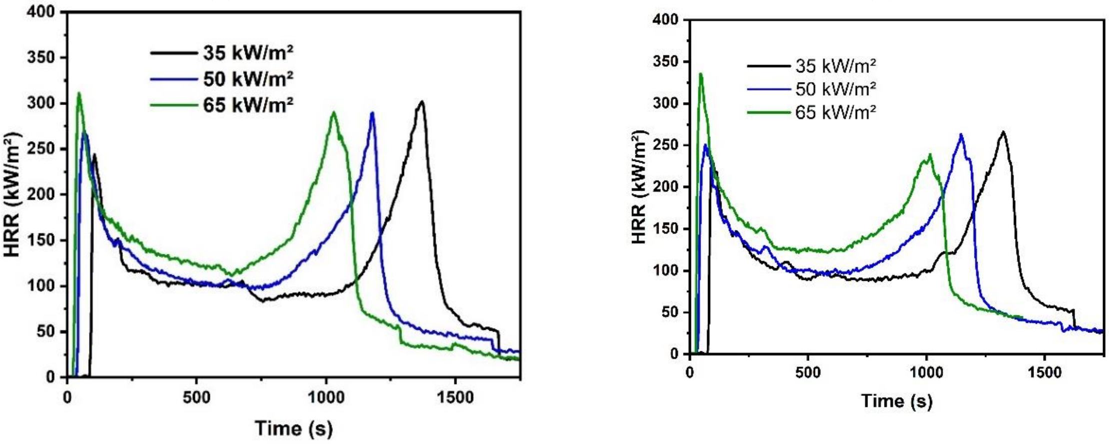
The graph reveals significant differences in ignition time, as well as the time to reach the first and second peaks. Moreover, there are notable disparities in average MLR and total HR, as evidenced by comparing the quantitative data from Table 9 and Table 3, which illustrate the different fire property parameters of Jointed Beech wood under 35, 50, and 65 kW/m^2.

Figure 23 : Residues of the burned hard wood under 35 kW/m^2 (Beech)

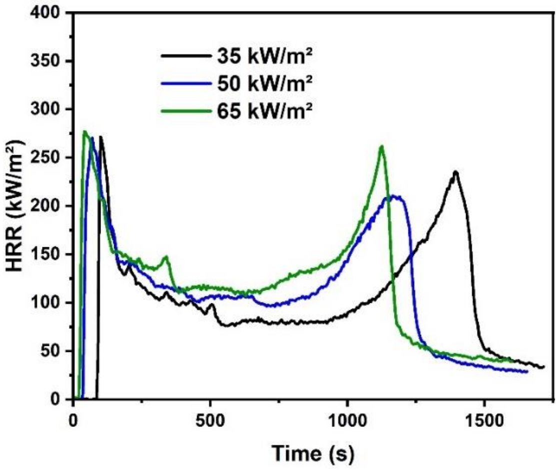
Furthermore, upon observing the fire behaviour of various joint wood species, it can be concluded that different heat exposures changed the curve patterns systematically. Though, in terms of quantitative data, the differences are observed in ignition time, total flaming time and the peak heat release rate. The changes in peak HRR also vary for wooden species based on the nature of the wood. Additionally, similar crack patterns are observed in residue under different heat exposure variations.



(a) No Joint (b) Butt Joint



(c) Half Lap Joint (d) 3 Finger Joint



(e) 6 Finger Joint

Figure 24 : HRR of Beechwood exposed to different heat fluxes (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint

Table 9: Fire behaviour properties of Beech Wood in different heat fluxes.

	Beech									
	No Joint		**Butt Joint**		**Half Lap Joint**		**3 Finger Joint**		**6 Finger Joint**	
	35	**65**	**35**	**65**	**35**	**65**	**35**	**65**	**35**	**65**
Ignition Time (s)	63±11	21±3	66±8	20±1	80±7	20±1	74±1	21±2	80±6	20±0
Flameout Time (s)	1403±18	1050±14	1345±42	1133±74	1403±32	1090±42	1418±46	1095±21	1443±18	1168±4
Flaming time (s)	1340±8	1029±17	1280±2	1113±73	1323±3	1071±42	1344±2	1075±23	1363±3	1148±4
Time to 1st Peak(s)	98±11	48±4	103±4	45±1	103±4	35±14	98±4	48±4	98±4	43±4
First Peak HRR (kW/m^2)	228±8	299±1	223±23	314±15	227±24	285±57	225±11	329±11	266±9	297±28
Time to 2nd Peak (s)	1310±28	1010±7	1295±42	1048±67	1333±53	1028±4	1345±28	1008±11	1375±28	1118±11
Second Peak HRR (kW/m^2)	271±28	271±19	286±11	239±1	297±8	296±8	264±4	242±4	226±15	253±13
Average MLR (g/s)	0.108±0.004	0.145±0.003	0.113±0.004	0.138±0.005	0.114±0.004	0.147±0.002	0.108±0.004	0.142±0.005	0.107±0.004	0.140±0.011
Initial Density (kg/m^3)	763±10	782±13	777±2	780±7	814±19	824±19	784±0	794±20	796±33	806±6
Total HR (MJ/m^2)	159±8	166±3	164±2	168±4	169±3	175±6	168±2	172±0	158±3	172±5

4.2 Fire Stability in Fully Developed Fire

Another important predefined goal was to analysis the fire stability of the wooden sample in the fully developed fire. This section is subdivided into three different sub section. In the first section, the influence of different wood types will be examined. Then, the performance of different joints on each type of wood will be compared. Finally, in the last part, the effect of thickness difference will be analysed.

4.2.1 Wood Species Influence

The following section will investigate and compare the influence of wood species in bench-scale fire stability tests. Table 18 presents an overview of the fire stability analysis of different wood types, namely Beech, Pine, and Spruce wood. The parameters presented in the table are the failure time of the wooden sample, the temperature during failure, and the charring rate of the wooden sample without joints. In this research, the charring rate was determined from temperature profiles within the timber. When the timber was exposed to fire, the temperature profile through the cross-section was used to estimate the depth at which charring occurred. Subsequently, the charring depth was divided by the time taken for that depth to become charred, thus calculating the charring rate.

Table 10: Overview of Fire Stability Analysis of different wood

Species	**Failure Time (min)**	**Failure Temperature**				**Charring Rate (mm/min)**	
		T1- 5 mm	**T2- 10 mm**	**T3- 15 mm**	**T4- 20 mm**	**5mm**	**10 mm**
Beech	26.3 ± 1.7	716±68	564±46	534±33	440±69	0.57±0.05	0.64 ± 0.01
Pine	24.4 ± 0.7	640±24	535±62	478±79	437±40	0.47±0.09	0.63 ± 0.01
Spruce	36.9 ± 3.7	527±20	407±88	344±111	300±229	0.34±0.01	0.37± 0.07

The failure time of the sample is measured through visual observation and with the assistance of a stopwatch. It has been observed that the failure time of Pine and Beech is lower than that of Spruce wood. Additionally, the charring rate of Pine and Beech is higher compared to Spruce wood. Despite Beech having a higher density than Pine and Spruce, the results for Beech and Pine wood are similar due to the thermal conductivity of the wooden sample. According to the literature, the thermal conductivity of Beechwood is 0.18 $Wm^{-1}K^{-1}$, Pinewood ranges from 0.12 to 0.17 $Wm^{-1}K^{-1}$, and Spruce wood ranges from 0.11 to 0.12 Wm^{-}

^{1}K^{-1} [14]. Since Beech and Pine wood can have similar thermal conductivity values, while Spruce has comparatively lower thermal conductivity, the heat transfer through Beechwood and Pine wood occurs faster than through Spruce wood.

Another reason of this failure time is the burning behaviour of the wood, as the spruce has longer flaming time because of the cracks formed in the spruce is different than the other two types of wood. By nature, Pine, and Beech has introduced smaller cracks in the surface which allowed the heat to transfer through sample as shown in Figure 25 (a) and (b), but Spruce wood introduced bigger and deeper cracks as shown in Figure 25 (c) in the surface of the specimen in this set up which changed the direction of the fire and the does not pass through uniformly through the sample. Also, in previous section 4.1.1 it has been seen that, the residue of the Spruce wood was stronger than the Pine and Beech. So, combining all the minor effects overall in this setup Beech and Pine failed faster than the spruce.

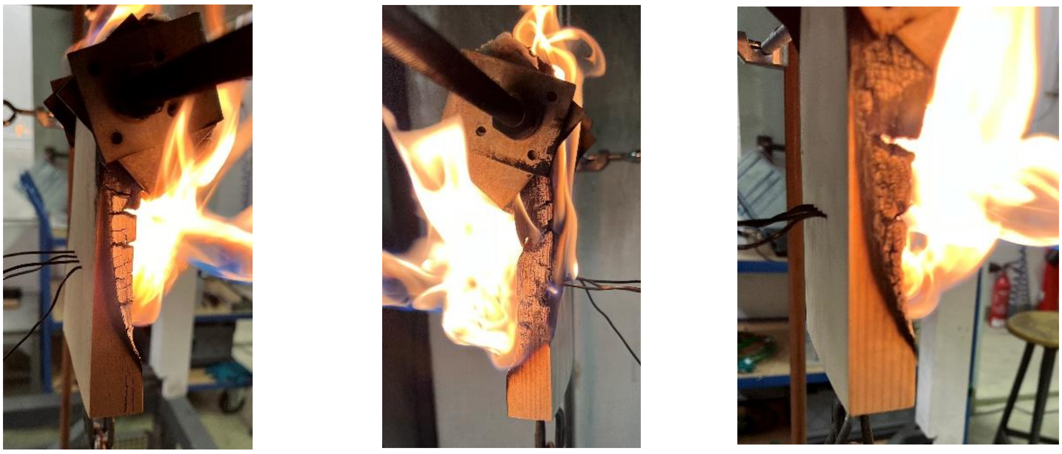


Figure 25 : The Burning of the Sample after 23 min (a) Beech, (b) Pine, and (c) Spruce

Figure 26 illustrates the temperature profile measured by in-depth thermocouples for the four different depths studied. Additionally, the temperature during the failure time of the different wooden samples has been provided in Table 10 above. It is observed from the temperature profile that Beech and Pinewood exhibit higher temperatures in the first 5 mm depth (T1) compared to Spruce wood. As the fire reaches the 10 mm depth (T2), Beech and Pine show similar temperatures, while Spruce shows lower temperatures. This behaviour is attributed to the thermal conductivity of the samples, as Beech and Pinewood have higher thermal conductivity than Spruce.

Also, the formation of char in the upper part of Pine and Beechwood is not dense enough to protect the inner layer. Consequently, by the 10 mm depth, they are exposed to fire directly, whereas, for Spruce, the upper char layer provides better insulation, resulting in lower temperatures. This is evident in the previous section 4.1 that the decrease in HRR was lower for Spruce wood after the formation of the char layer. This result is further supported by comparing the charring rate of the samples, where the charring rate of Beech and Pinewood is similar, whereas Spruce exhibits a lower charring rate.

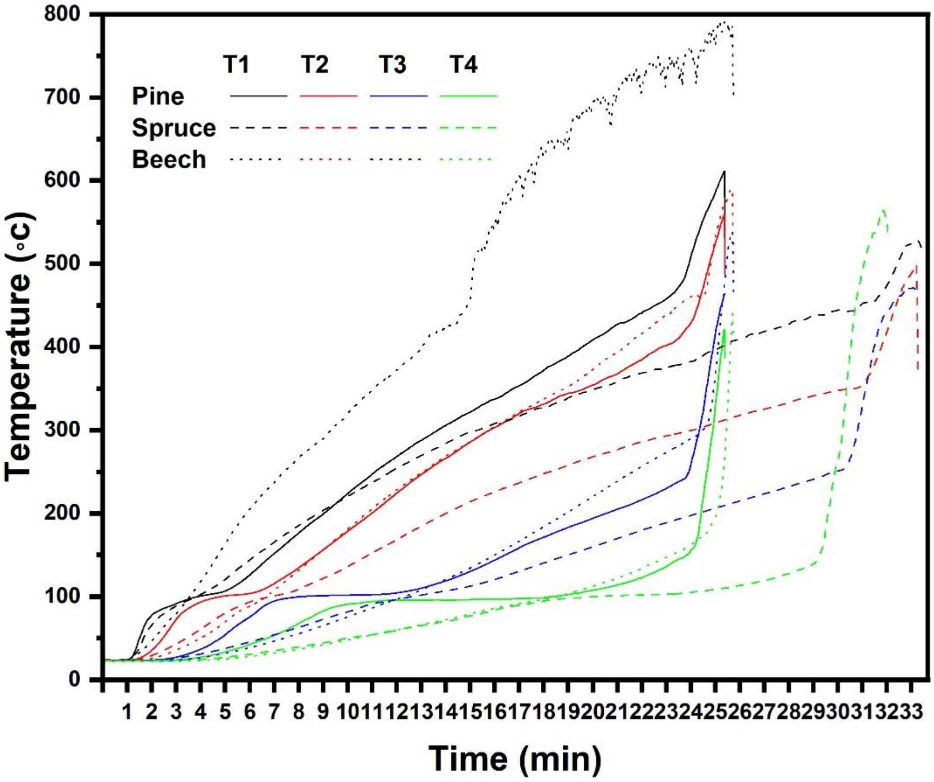


Figure 26 : Temperature Profile of Different Wood

Moreover, it concluded that the fire stability in the fully developed fire is not predominantly dependent on the density or the types of wood (Hardwood or Softwood). Instead, the main difference is observed due to the thermal conductivity of the wooden sample, as well as the char density of the wood. In addition to quantitative data, qualitative analysis also reveals effects in terms of the residue type of the wooden sample and the insulation provided by char layers for different types of wood.

4.2.2 Joint Type Effects

In this section, the effects of different joints in the fire stability have presented for the Beech, Pine, and Spruce wood respectively. The failure time (min), failure temperature (ºC) and the charring rate of the different jointed wooden samples will be compared.

Beech Wood

The overview of the fire stability test of Beechwood joints is depicted in Table 11, indicating that the failure time of Beechwood with and without joints ranges between 19-26 minutes. Similarly, the charring rate for these samples falls within the range of 0.52-0.66 mm/min. It concluded in section 4.2.1 that the variation in failure time and charring rate among different wooden samples is influenced by factors such as thermal conductivity, cracks, or openings on the surface of the sample.

As all jointed samples shown here are Beech woods, the thermal conductivity and char layer formation remain consistent across them. However, despite this uniformity, significant differences in failure are observed due to the presence of joints. Typically, joints are regarded as the weakest part of the sample. In the case of Beechwood, it is noted that all jointed samples fail at the glue line, whereas in the absence of joints, failure occurs near the upper part of the samples.

Table 11: Overview of Fire Stability Analysis of Beech Wood Joints

Beech Wood Joint Type	Failure Time (min)	Failure temperature (ºC)				Charring Rate (mm/min)	
		T1- 5 mm	T2- 10 mm	T3- 15 mm	T4- 20 mm	5 mm	10 mm
No Joint	26.3 ± 1.7	716±68	564±46	534±33	440±69	0.57±0.05	0.64±0.01
Butt Joint	22.6±2.8	578±84	361±62	257±46	157±32	0.45±0.02	0.52±0.10
Half Lap Joint	21.9±2.5	396±167	344±22	236±34	160±43	0.37±0.11	0.52±0.05
3 Finger Joint	19.0±0.8	627±55	408±22	247±63	167±56	0.51±0.04	0.66±0.01
6 Finger Joint	22.4±0.9	613±51	411±46	304±10	194±41	0.46±0.04	0.56±0.06

The Figure 27 shows the temperature profile of the samples in four different depths. Also, from this figure, the char depths of the specimens based on the positions of the thermocouples in relation to the time can be examined. This figure indicates that the charring rates were not constant, despite the indication that timber is completely turned into char when the temperature reaches 300°C. That means, when the thermocouple 1 reaches 300°C, this 5 mm of the wood considered as char and same goes for the other thermocouples as well. The difference in charring rates is evident in the first 5 mm depth (TC1) and 10 mm depth (TC2), as illustrated in Table 11, where the charring rates for both depths are presented. The difference in charring rates is noted between these two different depths.

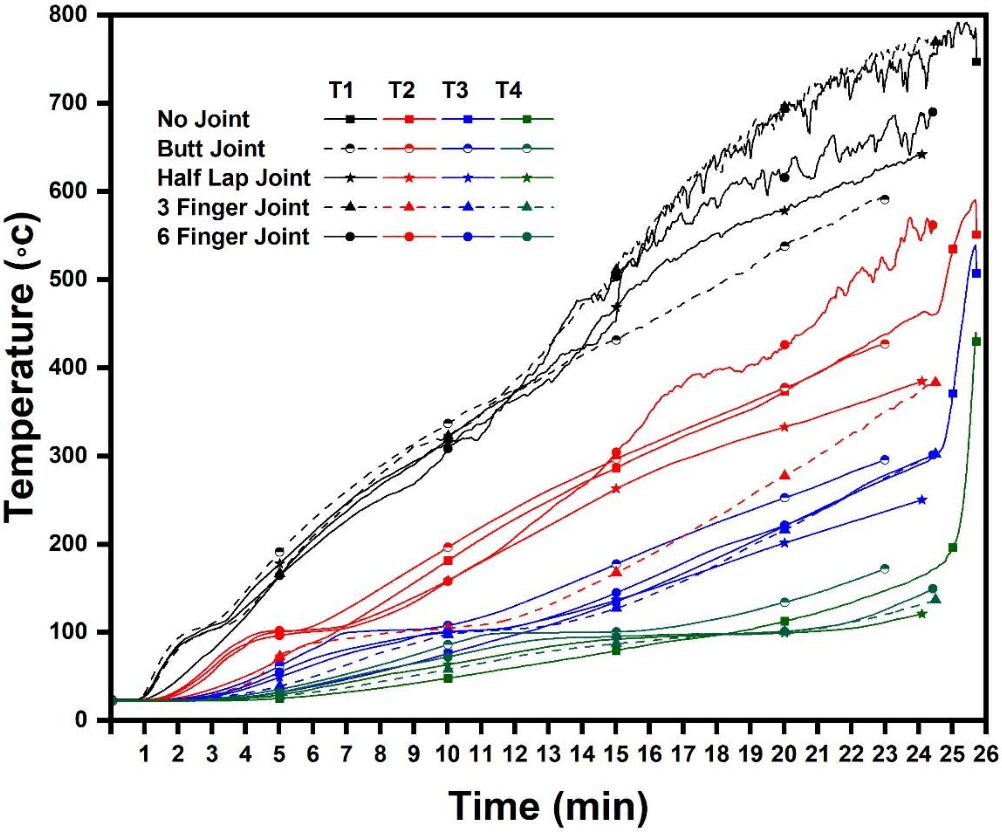


Figure 27 : Temperature Profile of Beech Wood Joints

Furthermore, the temperature profile reveals that in the jointed wooden sample, only 10 mm of char is produced during failure, whereas in samples without joints, failure occurs after the complete char of the wooden sample. The temperature during failure was similar for all the sample considering the uncertainty. There is no significance pattern due to different joint type. Additionally, it is noted that due to the presence of joints, there is not a significant difference in failure time in Beech wood. Yet, fluctuations in failure time are observed. Moreover, jointed woods exhibit variations in char production and fluctuations in heat transfer.

Pine Wood

Table 12 provides an overview of the fire stability test conducted on Pinewood. The failure time of Pinewood ranges between 22 and 25 minutes, while the charring rate varies between 0.53 and 0.64 mm/min. It is worth noting that this charring rate is determined based on the temperature of the wooden sample, as discussed previously.

Table 12: Overview of Fire Stability Analysis of Pine Wood Joints

Pine Wood Joint Type	Failure Time (min)	Failure temperature				Charring Rate (mm/min)	
		T1- 5 mm	T2- 10 mm	T3- 15 mm	T4- 20 mm	5 mm	10 mm
No Joint	24.2±0.7	640±24	535±62	478±79	437±40	0.47±0.09	0.63±0.01
Butt Joint	22.7±0.9	484±137	370±72	279±23	152±27	0.44±0.17	0.64±0.02
Half Lap Joint	24.2±2.8	516±182	391±54	266±54	131±27	0.40±0.13	0.55±0.02
3 Finger Joint	24.9±1.0	632±136	426±31	288±39	151±29	0.45±0.11	0.53±0.04
6 Finger Joint	24.3±0.4	670±37	479±116	285±28	151±27	0.48±0.02	0.61±0.05

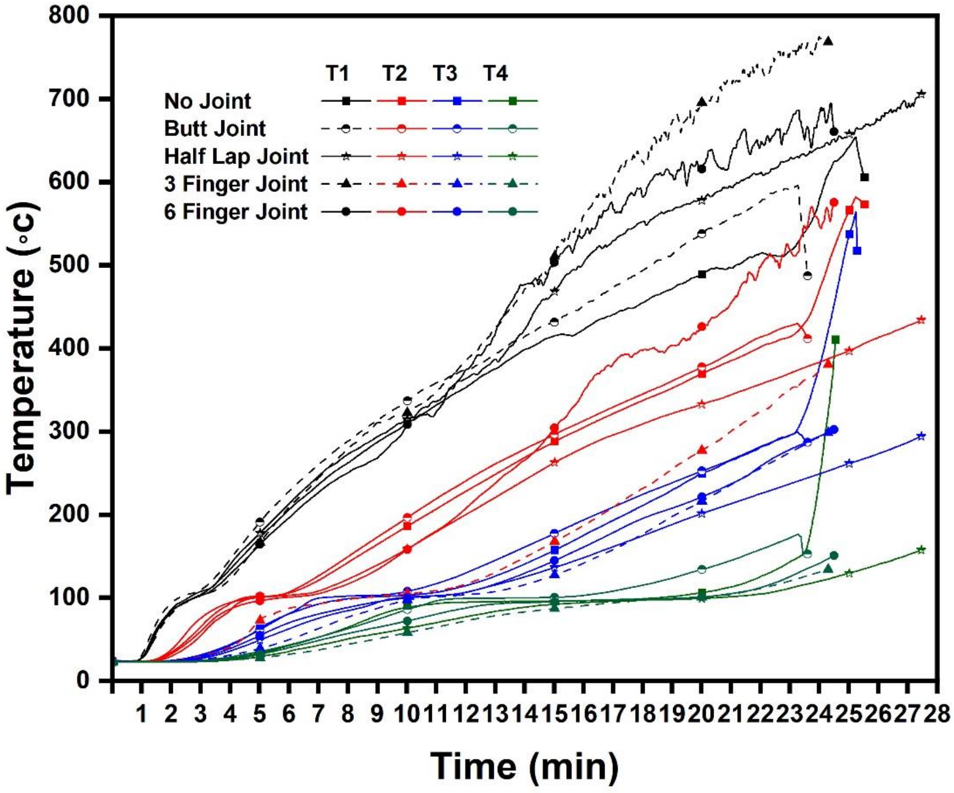


Figure 28 : Temperature Profile of Pine Wood Joints

In Figure 28, the temperature profile of the jointed Pine wood is depicted. Like Beechwood, Pinewood also forms char throughout the entire 24 mm thickness in samples without joints, whereas in jointed wood, failure occurs with only 10 mm of char present. This highlights that joints are indeed considered weaker points in any sample. In jointed wood fire followed the path of the joints, but without joint case fire has followed the grain and went to upper part. Thus allowed the wood to burn from the back as well. Overall, the 24 mm of the upper part of the sample became char.

Typically, in a wooden sample exposed to fire, continuous burning leads to the formation of char, and the sample fails through char degradation. When two parts are bonded together with glue, the glue line is deemed the weakest point. Consequently, sample failure occurs through the glue line, even if less than 50% of the char has formed.

Spruce Wood

Table 13 presents an overview of the fire stability test conducted on spruce wood joints. The failure time ranges between 27 and 40 minutes, while the charring rate varies from 0.37 to 0.47 mm/min. The failure temperature of the jointed wood is also included in the table. Considering the uncertainty, it is observed that joints do not follow a consistent pattern within a specific type of wood. Nevertheless, differences in failure time and heat transfer are noticeable due to the presence of joints.

Table 13: Overview of Fire Stability Analysis of Spruce Wood Joints

Spruce Wood Joint Type	**Failure Time (min)**	**Failure temperature**				**Charring Rate (mm/min)**	
		T1- 5 mm	**T2- 10 mm**	**T3- 15 mm**	**T4- 20 mm**	**5 mm**	**10 mm**
No Joint	36.9±3.7	527±20	407±88	344±111	300±229	0.34±0.01	0.37± 0.07
Butt Joint	29.0±1.5	522±42	362±46	262±35	154±32	0.40±0.02	0.41±0.07
Half Lap Joint	33.2±3.3	516±43	345±56	267±10	157±18	0.33±0.04	0.47±0.10
3 Finger Joint	29.8±2.2	633±49	446±34	291±16	170±12	0.43±0.03	0.47±0.10
6 Finger Joint	34.3±1.9	583±13	411±35	326±48	264±151	0.42±0.05	0.47±0.03

Figure 29 illustrates the temperature profile of Spruce wood, exhibiting a similar phenomenon as observed in Pine and Beechwood, as discussed earlier. Additionally, in all jointed Spruce samples, failure occurs at the glue line, whereas in samples without joints, failure is attributed to char degradation.

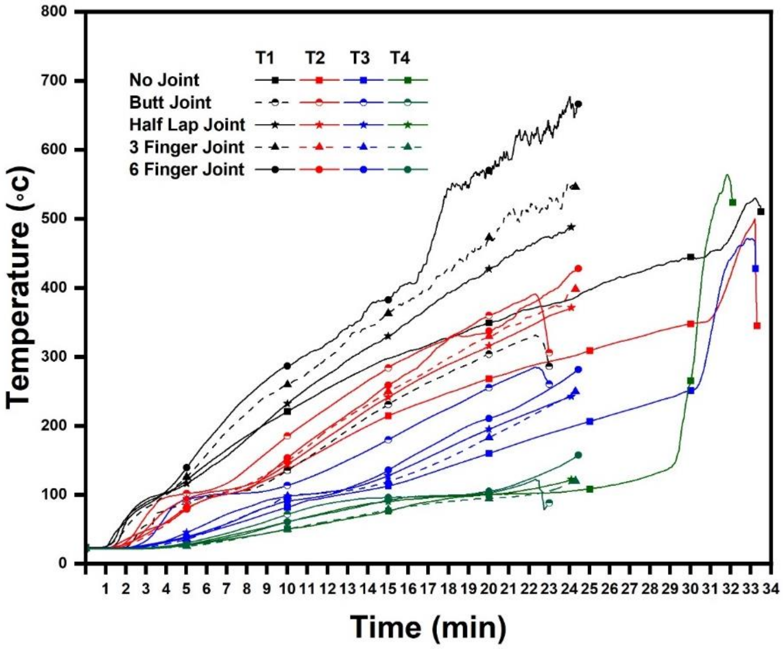


Figure 29 : Temperature Profile of Spruce Wood Joints

Overall, by observing the 5 different joints of Beech, Pine and Spruce it concluded that Spruce took longer time to fail than Pine and Beech. The joint behaviour of each type of wood is dominated by the individual wood type behaviour. Figure 30 depicts the failure time with uncertainty, and it is seen that the failure time is not significantly different for the jointed wood. But fluctuation in failure time has been observed due to the joints.

Also, the failure temperatures of the wood with joints show similar temperature values for each of the wood. However, there are some similarities observed for Pine and Beechwood as they had similar thermal conductivity and spruce took a longer time to fail due to thermal conductivity and density. But for the joints, the temperature profile doesn’t show any differences. Another reason for this failure time and temperature profile difference is the char or crack formation of the jointed wooden sample. The burning process of different wooden samples in the fire stability test is shown in Appendix IV. By qualitative observation, it is also evident that different wood behaves differently in terms of forming the cracks. Which results in the transfer of heat through the sample, even sometimes changing the direction of the fire.

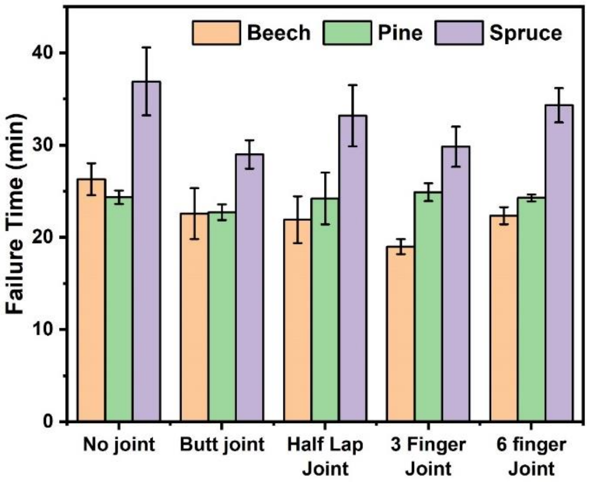


Figure 30 : Failure Time of Different Wood

The significant parameter in this fire stability test was the charring rate. Figure 31 displays the charring rate of Spruce, Pine, and Beech wood based on their density. Without joints, the charring rate for the first 10 mm depth is 0.37± 0.07, 0.63±0.01, and 0.64±0.01 respectively for Spruce, Pine, and Beech wood. These charring rates are compared with the relationship between charring rate and density found in the literature [43] . The comparison reveals that the charring rates for Pine and Beech wood fall within the range suggested by the literature, whereas for Spruce wood, the charring rate is comparatively lower.

Furthermore, upon comparing with jointed wood, it becomes evident that the fluctuation in the charring rate is increased in jointed wood. Typically, the charring rate is expected to decrease with increasing timber density [43]. In this setup, the charring rate fluctuates with the fluctuation of heat transfer through the sample, which dominated by the cracks and joints in the wooden sample along with variations in wood conductivity.

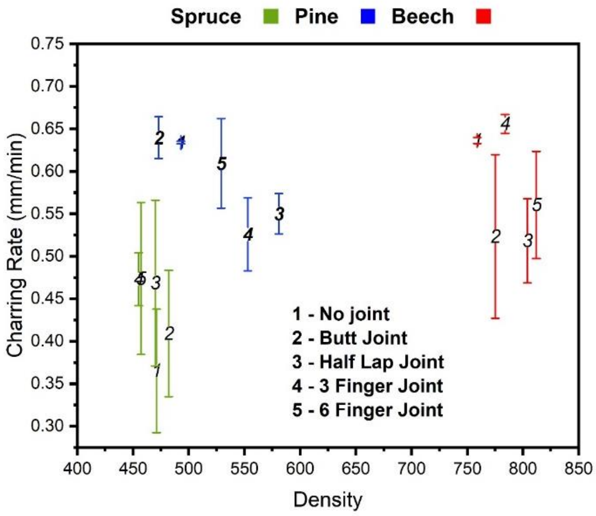


Figure 31 : Charring Rate and Density Relationship of Different Wood at 10mm depth

4.2.3 Thickness Impact

In this section, the impact of thickness on fire stability is being examined. Table 14 analyses the parameters of the fire stability test for spruce wood joints with a thickness of 42mm. It is observed from the data that the failure time without joints exceeds that of jointed wood. Despite considering uncertainties, the failure temperature appears consistent across all wooden samples. The charring rate fluctuates between 0.37 to 0.47 mm/min in the 42 mm spruce wood.

Table 14: Overview of Fire Stability Analysis of Spruce 42mm wood joints

Spruce 42 mm Wood Joint Type	**Failure Time (min)**	**Failure temperature**				**Charring Rate (mm/min)**	
		T1- 5 mm	**T2- 10 mm**	**T3- 15 mm**	**T4- 20 mm**	**5mm**	**15 mm**
No Joint	84.0±14.5	807±17	585±57	398±82	231±52	0.34±0.06	0.37±0.03
Butt Joint	61.2±5.3	842±57	556±66	346±28	183±32	0.41±0.07	0.45±0.06
Half Lap Joint	62.6±1.0	690±110	475±34	299±18	142±21	0.38±0.10	0.38±0.04
3 Finger Joint	63.9±6.5	847±66	714±163	522±158	269±120	0.41±0.07	0.47±0.05
6 Finger Joint	68.1±2.6	825±94	577±64	372±25	171±1	0.37±0.06	0.42±0.05

The sample without joint usually burnt from the upper part and due to the break in char, which took longer time to burn the wooden sample compared to the jointed wood. In jointed wood, it is found that the joints failed faster through glue line the as the glued jointed part are the weakest point. But for 42 mm the half lap joint doesn’t fail from the glue line though the other joints failed from the glue line. Because during the burning of the half lap joint a big crack is observed in the upper jointed part which led to change the direction of the fire thus occurs failure in the half lap joint above the glue line. Figure 32 shows the residue picture of the 42 mm half lap sample which showed the big crack in the sample.

Overall, by observing the different thickness of spruce wood, it summarised that, the 24 mm thickness wood failure faster than 42 mm because of the thickness difference. This is also evident from Figure 33 where the comparison of the failure time of two different thickness is presented.

Figure 32: Burning process and the residue of the 42mm Spruce wood (Half Lap Joint).

The charring rate comparison has been found in Figure 34. Considering the uncertainty and overlapping of the charring rate of spruce wood is between 0.3 - 0.6 mm/min. Though in literature for softwood, the charring rate lies between 0.5-0.8 mm/min [43].

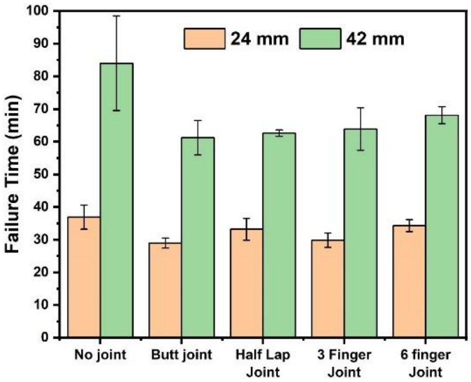


Figure 33: Failure Time of Different Wood thicknesses

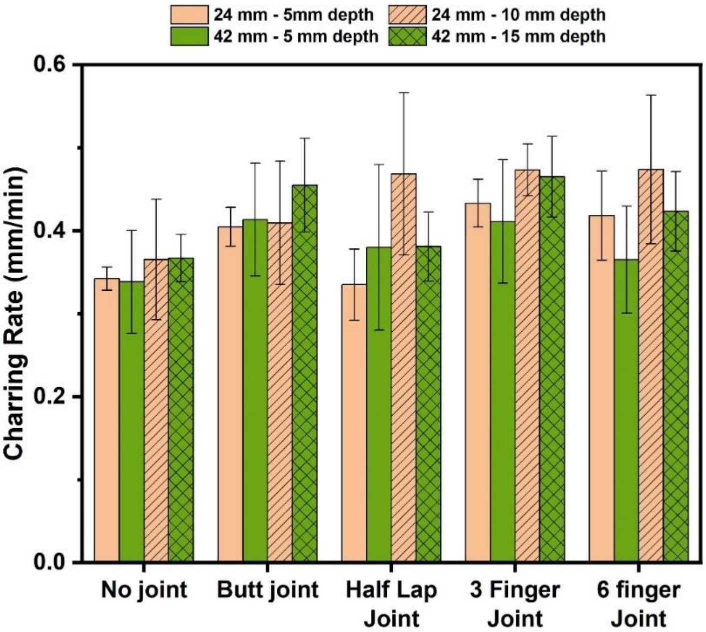


Figure 34 : Charring Rate comparison

Chapter 5 Conclusions

An experimental study was conducted in which 3 different species of wood and 5 different types of joints were used as a primary variable. The goal of this research was to investigate the fire behaviour under developing fire and the stability of these samples in fully developed fire. Besides the primary variable, another thickness of Spruce wood was examined. Moreover, to understand the differences in behaviour different heat exposures were compared in the fire tests.

This study focused on the bench scale test to understand the fire behaviour of the jointed wood samples. Though the different wood species' performances were found in previous studies, the novelty of this research work is the assessment of different glued-jointed timber samples. To understand the jointed wood, it was important to understand the behaviour of the different wood species. The most important findings that address the objectives will be explained in the following:

- The investigation determined the differences between hardwood and softwood in the fire behaviour. Softwood ignites faster than hardwood due to the density difference. But Pine and Beech have shown shorter flaming time than Spruce. However, the formation of cracks, char production, and the behaviour of wood are significantly different in these 3 species of wood.
- For the wood with joints, the main difference is observed in the second peak HRR. Though the second peak heat release graph pattern is similar, the time to reach the second peak is significantly different for different jointed wood. The difference in time to reach the second peak is observed in Pine and Beechwood, whereas for Spruce wood, no difference is observed in time to reach the second peak due to the joints. For Beech and Pinewood, the joints have been seen to hold the sample together during the deformation of the sample, which creates a difference in the second peak behaviour of the jointed samples. Overall, the combined effect of second peak heat release and the performance of the wood act as a dominant factor in reaction to fire for jointed wood.
- Due to the different heat exposure, the curve patterns are observed to change systematically. However, in terms of quantitative data the differences are observed in ignition time, total flaming time and the peak heat release rate.

- The fire stability in the fully developed fire is not predominantly depending on the density or the types of wood (Hardwood or Softwood). Instead, the main difference is observed due to the thermal conductivity of the wooden sample, as well as char density of the wood. The qualitative analysis also reveals effects in terms of the residue type of the wooden sample and the insulation provided by char layers for different types of wood.
- All the jointed wood failed from the glue line for the sample with 24 mm thickness. Failure time of Beech and Pine is shorter than Spruce. However, the failure time is not significantly different for each type of jointed samples. But fluctuation has been observed due to the joints. Spruce took longer time reach failure compared to the Pine and beech wooden due to thermal conductivity and density.
- The residues are more fragile for Beech wood compared to Pine and Spruce wood. Also, during burning deformation and shrunken behaviour is observed in Beech and Pine wood respectively.
- In fire stability, the charring rates for Pine and Beech wood without joints are within the standard charring rates whereas for Spruce wood charring rate is comparatively lower, which indicates slower thermal penetration through spruce.
- In the jointed wood, 10 mm char depth have found during failure where in without joint in the time of failure the 24 mm char depth have found.
- The HRR graph pattern is similar in both thicknesses, but in terms of total heat release, burning time differences are observed. For the fire stability test, it is found that in 24mm thickness wood failure is faster than 42mm. Failure for both thicknesses was observed from the glue line except for the half-lap joint of 42 mm Spruce wood.

There is a high demand for understanding the behaviour of the wood, and new knowledge has been provided by the current investigation. By achieving a deeper understanding, it may be possible to improve the prediction of the burning behaviour of wooden structures. To increase the understanding of the jointed wood behaviour in fire conditions, further research could be directed to address the following:

- Conduct experiments that simulate realistic fire scenarios This would help validate findings from small-scale tests and provide insights into how jointed timber structures perform in practical fire situations.

- Further investigate the underlying mechanisms responsible for jointed timber failure, with a focus on factors such as glue line performance, heat transfer mechanism. Advanced analytical techniques, such as microscopy and thermal imaging, could be employed to gain deeper insights into these processes.
- Assess the effectiveness of retrofitting techniques aimed at improving the fire resistance of existing jointed timber structures. This could include adding fire-resistant materials or reinforcing joints to enhance overall structural integrity and safety.

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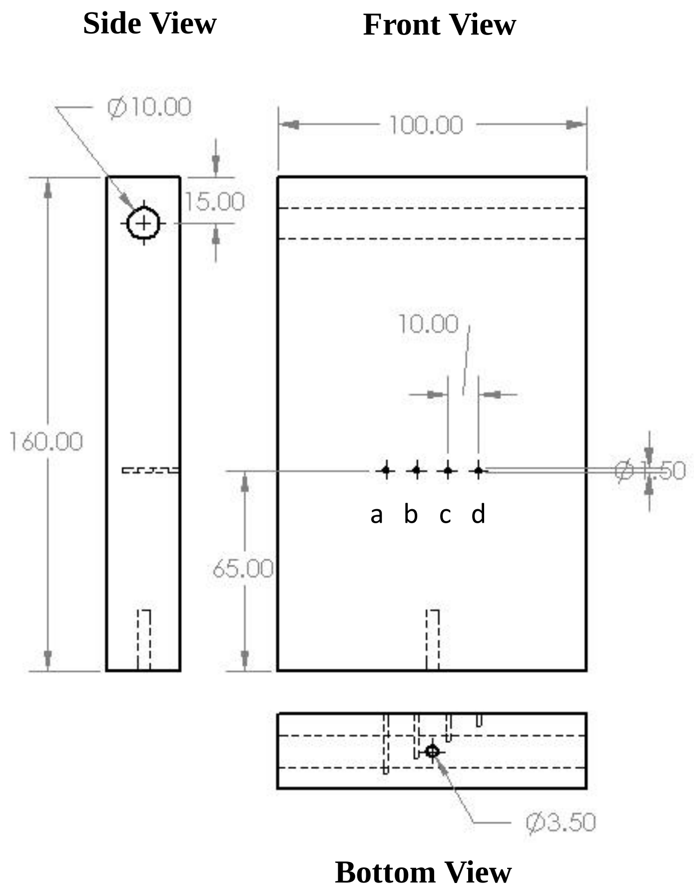
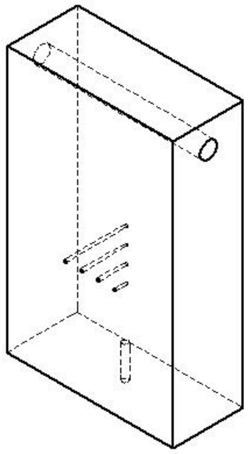
Appendix I Thermocouple positions

- **24 mm**



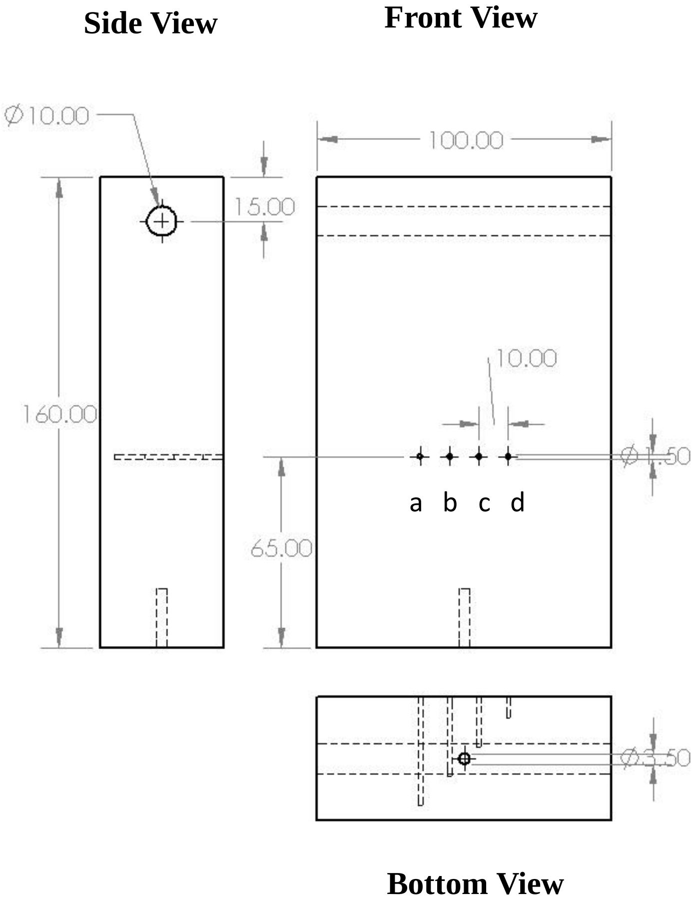
(A) View With Dimensions

Drill Depth for 4 thermocouples: a) 19 mm b) 14 mm c) 9 mm, and d) 4 mm.



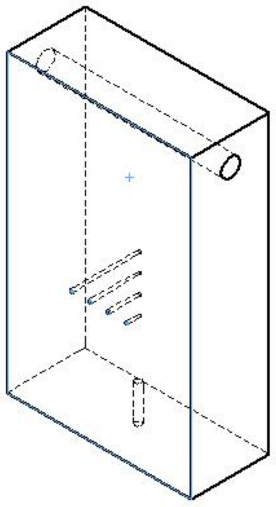
(B) Isometric View of the 24 mm Drilled Sample

- **42 mm**



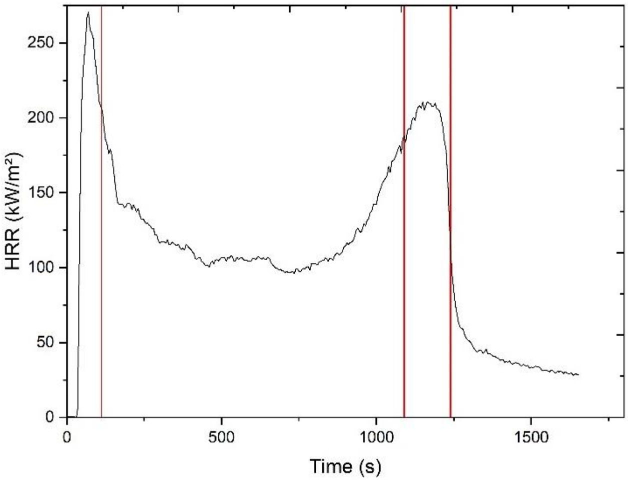
(A) View With Dimensions

Drill Depth for 4 thermocouples: a) 37 mm b) 27 mm c) 17 mm, and d) 7 mm.



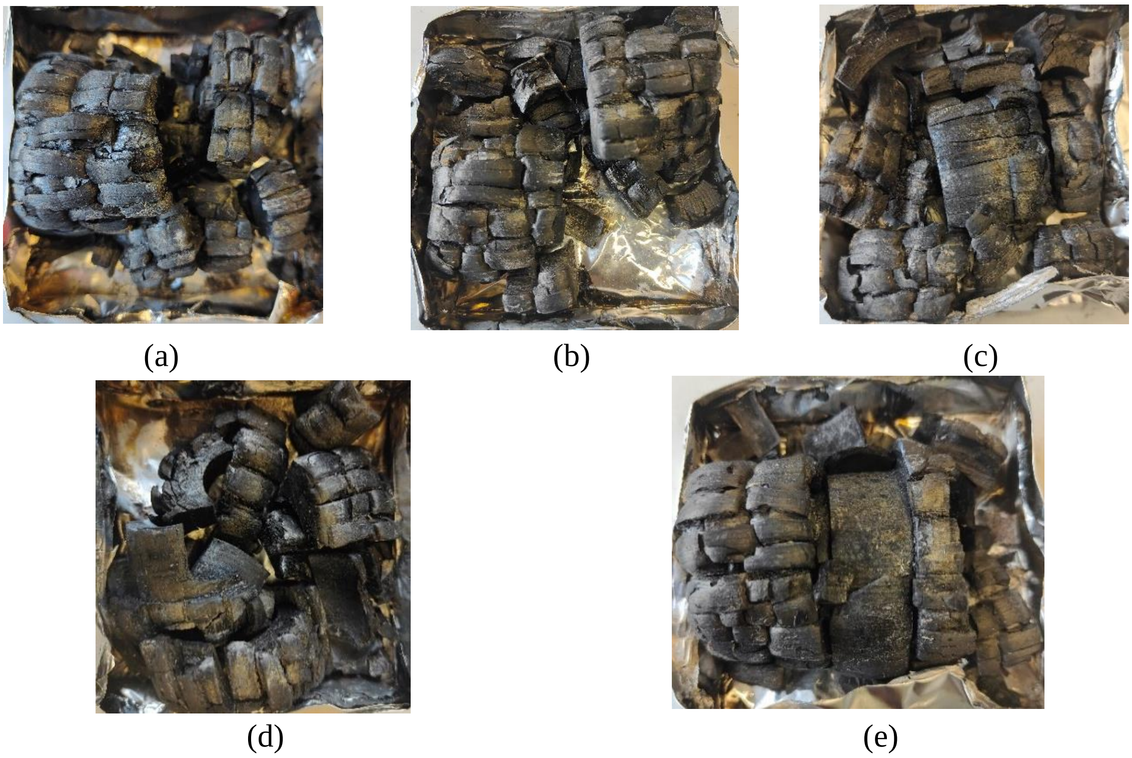
(B) Isometric View of the 42 mm Drilled Sample

Appendix II Effective Heat of Combustion (EHC) Comparison



	Sample Description	Test 1				Test 2			
		First Peak		Second Peak		First Peak		Second Peak	
		Start	End	Start	End	Start	End	Start	End
1	Pine	25	55	850	1130	25	65	1040	1150
2	Pine - Butt Joint	20	55	970	1170	20	50	1065	1155
3	Pine - Half Lap Joint	20	60	1005	1265	20	50	1120	1255
4	Pine - 3 finger Joint	20	50	1110	1270	20	60	1130	1260
5	Pine - 6 finger joint	20	60	1090	1320	20	50	1210	1280
6	Spruce	25	60	1155	1365	20	60	1285	1410
7	Spruce - Butt Joint	20	55	1160	1390	20	40	1255	1365
8	Spruce - Half Lap Joint	15	45	1150	1360	20	50	1205	1345
9	Spruce - 3 finger Joint	15	45	1055	1355	20	50	1225	1380
10	Spruce - 6 finger joint	15	45	1050	1320	20	40	1200	1385
11	Beech	30	110	970	1210	35	105	1145	1175
12	Beech - Butt Joint	30	95	1030	1180	35	95	1115	1155
13	Beech - Half Lap Joint	35	95	1145	1215	35	100	1135	1225
14	Beech - 3 finger Joint	30	100	1080	1210	35	105	1140	1245
15	Beech - 6 finger joint	30	110	1090	1240	35	85	1215	1250

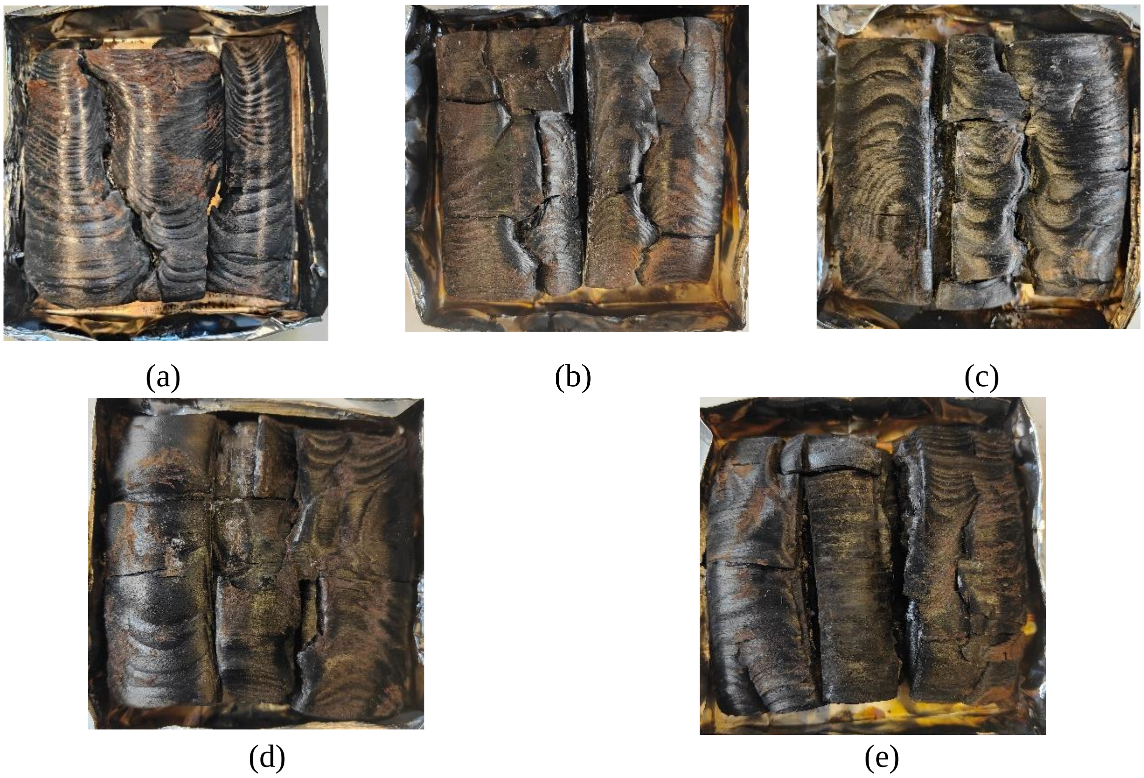
Appendix III Residue of different jointed wood under 50 kW/m^2



(a) (b) (c)

(d) (e)

Figure: Residues of different Joints of Beech wood (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint



(a) (b) (c)

(d) (e)

Figure: Residues of different Joints of Pine wood (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint

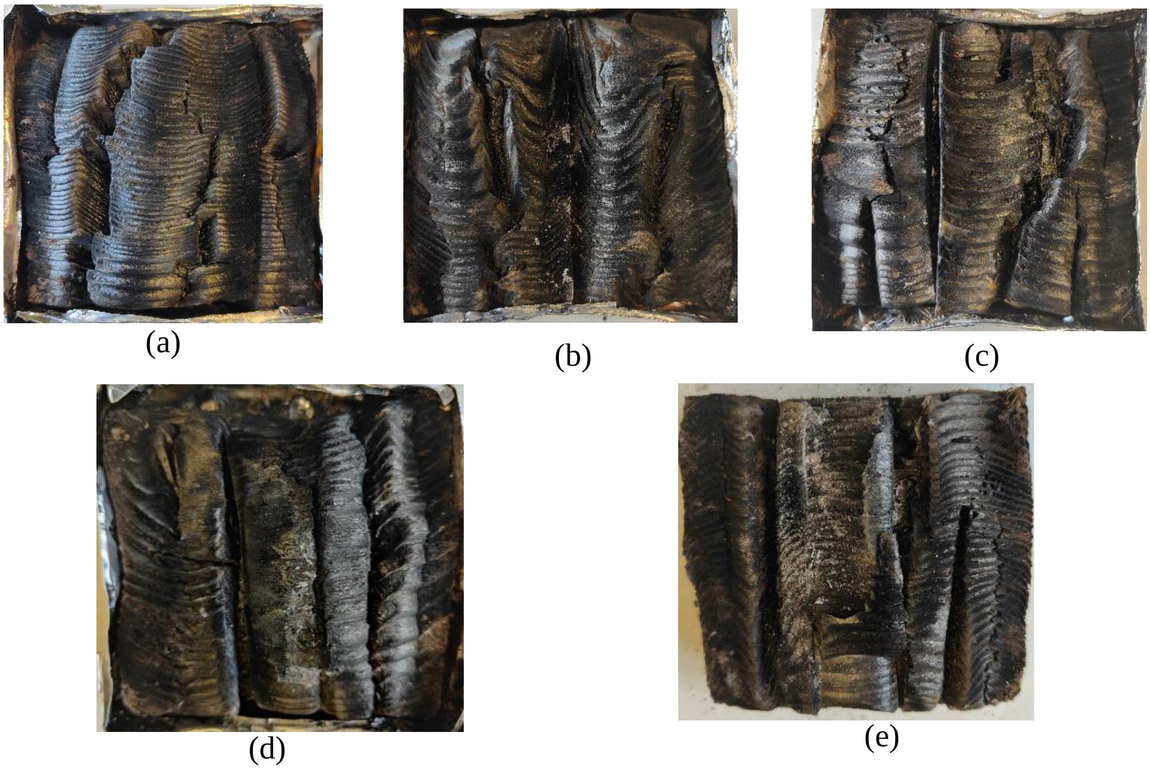


Figure: Residues of different Joints of Spruce 24mm wood (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint

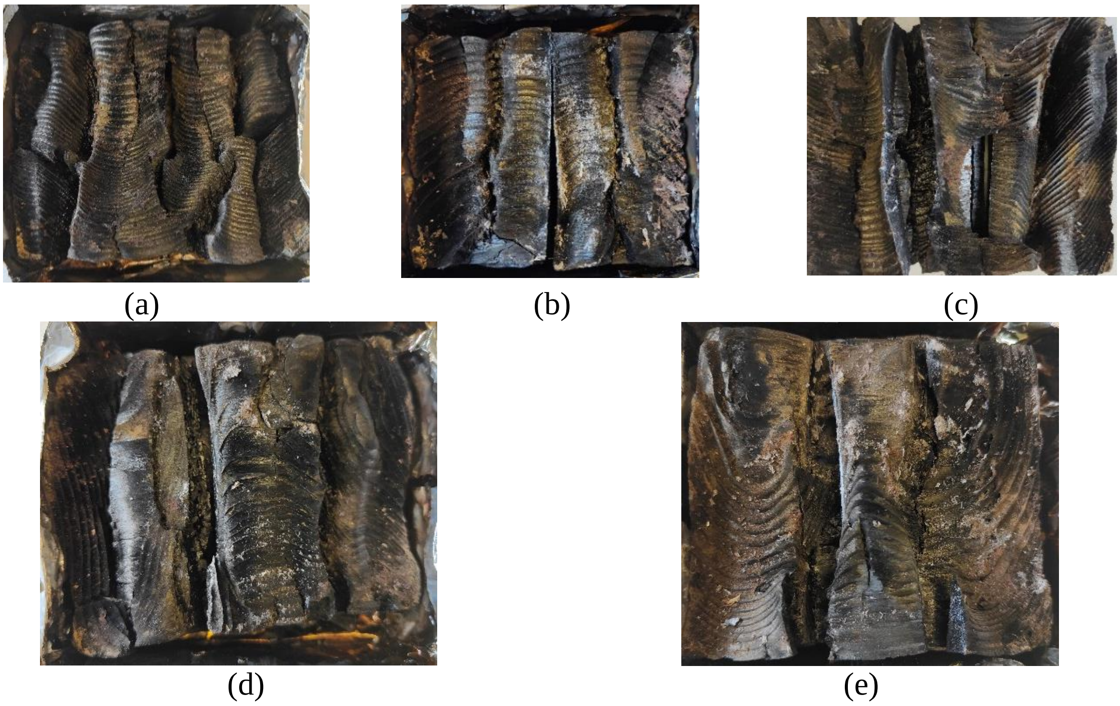


Figure: Residues of different Joints of Spruce 42mm wood (a) No Joint, (b) Butt Joint, (c) Half Lap Joint, (d) 3 Finger Joint, and (e) 6 Finger Joint

Appendix IV Residue of different jointed wood under 65 kW/m^2

Figure: Residues of different Joints of Beech wood

Figure: Residues of different Joints of Pine wood

Figure: Residues of different Joints of Spruce 24mm wood

Appendix V Burning process in fire stability test

No Joint

(a) Beech **(b) Pine** **(c) Spruce**

Figure: No Joint After 23 min of the Test (a) Beech, (b) Pine, (c) Spruce

Butt Joint

(a) Beech **(b) Pine** **(c) Spruce**

Figure: Butt Joint After 23 min of the Test (a) Beech, (b) Pine, (c) Spruce

Half Lap Joint

(a) Beech **(b) Pine** **(c) Spruce**

Figure: Half Lap Joint After 23 min of the Test (a) Beech, (b) Pine, (c) Spruce

- **3 Finger Joint**

(a) Beech **(b) Pine** **(c) Spruce**

Figure: 3 Finger Joint After 18 min of the Test (a) Beech, (b) Pine, (c) Spruce

- **6 Finger Joint**

(a) Beech **(b) Pine** **(c) Spruce**

Figure: 6 Finger Joint After 18 min of the Test (a) Beech, (b) Pine, (c) Spruce