FIRE RESISTANCE OF PARTIALLY PROTECTED CROSS-LAMINATED TIMBER ROOMS

by

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ABSTRACT

This thesis studies the fire behaviour of Cross Laminated Timber (CLT) panels in partially protected rooms. A one-dimensional heat transfer model was developed to determine the fire resistance of CLT floor and wall panels. During this study, three room fire tests were conducted at Carleton University Fire Research Laboratory to determine the maximum percentage of unprotected CLT surface area that will yield similar results to that of a fully protected room. The rooms had a single opening and were constructed entirely using 3-ply, 105 mm thick CLT panels. A non-standard, parametric fire using furniture and clothing as fuel was used and 2 layers of gypsum board were used to cover the ceiling and the protected walls. The Heat Release Rate, temperature, charring rate and gypsum falloff time of each test was collected. The results obtained from the room test were then compared to the numerical heat transfer model to evaluate its accuracy.

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Nomenclature

A Surface area, m^2

c Specific heat capacity, $J\ kg^{-1}\ K^{-1}$

F_b Factored bending strength, MPa

f_b Specified strength in bending, MPa

Fo Fourier number

h_f Convective heat transfer coefficient in fire, $W\ m^{-2}\ K^{-1}$

h_∞ Convective heat transfer coefficient in ambient air, $W\ m^{-2}\ K^{-1}$

k Thermal conductivity, $W\ m^{-1}\ K^{-1}$

K_D Load duration factor

K_H System factor

K_L Lateral stability factor

K_{Sb} Service condition factor

K_T Treatment factor

K_{zb} Size factor in bending

m Mass, kg

M_f Bending moment resistance, N m

M_r Factored bending moment resistance, N m

q''_{fire} Heat flux from fire, $W\ m^{-2}$

$\dot{q}_G$	Internal heat generation, W m^{-3}
S	Section modulus, m^3
t	Time, s
Δt	Time step duration, s
T	Temperature, °C
T_f	Temperature of the fire, °C
T_∞	Temperature of ambient air, °C
Δx	Control volume size, m

1 INTRODUCTION

As the world's desire for renewable resources continues to grow, as too does the research in heavy timber construction. Heavy timber construction is the method of creating engineered framed structures using heavy timber jointed together. Heavy timber products are properly designed to have high load bearing characteristics that allows them to compete with other building materials, such as concrete and steel. Heavy timber construction has created a lot of interest due to inherit material advantages such as:

- Erecting time is reduced due to the ability to prefabricate structural members, whole walls and sections of floor slabs.
- Ability to create sandwich panels of timber and rigid insulation for high R-values.
- Using the lamination process, recycled or imperfect timber may be used.
- Because wood is structurally strong, light and flexible, it has a natural ability to endure and absorb seismic loads.
- Large timber members have performed well structurally under fire conditions due to their natural ability to char, allowing the unaffected cross-section to remain at room temperature therefore maintaining their full strength.

Perhaps one of the biggest advantages of this type of construction is that wood is a renewable resource. Wood is a sustainable and eco-friendly building material that provides a well balance construction building model.

Throughout civilization, wood has been one of the main construction materials used by society. In recent times, the use of heavy timber construction is seen in schools, auditoria, churches and many other buildings that have large open spaces. With the constant pursuit of renewable resources, wood has once again started to be considered as a main structural material for the construction of midrise buildings and also for non-residential housing. The focus of this study is on the use of heavy timber products, especially Cross-Laminated Timber in midrise buildings. The differences between light frame and heavy timber are identified and more clearly explained later in this thesis.

1.1 Statement of the Problem

Heavy timber products such as Cross-Laminated Timber (CLT), Parallel Strand Lumber, Laminated Veneer Lumber and others, have been developed to perform similar to concrete and steel when being used as main structural members of midrise buildings. Studies are currently being conducted by the NEWBuildS research network [**1**], on these heavy timber panels for their structural, vibration, sound insulation, environmental, and fire performance. This research project studies the behaviour of CLT panels at elevated temperatures and its resistance as a structural component in midrise buildings.

One of the biggest concerns regarding the use of heavy timber panels in midrise and tall buildings is the fire risk associated with this combustible construction material. The National Building Code of Canada (NBCC) [**2**] Division B Part 3 and Part 9 currently limit buildings constructed using combustible materials to a maximum of 4 storeys with a maximum floor area of 1800 m^2 per storey. This restriction provides great limitations to engineers and architects wishing to design wood buildings. It is important to note that the NBCC requirements were derived by considering light frame timber as the main type of combustible construction. The fact is that solid heavy timber panels used for floors and load carrying walls do not possess the same fire characteristics as light frame timber walls found in low-rise residential buildings.

1.2 Study Objectives

The objective of this thesis is to study the behaviour of CLT panels at elevated temperatures in a room application. Through the completion of three room fire tests while gathering heat release rate, wall and room temperature data, the objective is to provide a better understanding of the fire performance of CLT. In order for CLT construction to be considered safe at elevated temperatures in a building application, it must meet or surpass certain requirements. Structurally, it must sustain the load throughout the NBCC specified fire duration. It must contained the fire in the compartment of origin and limit fire spread to other compartments.

This study will examine different combinations of gypsum board fire protection for CLT walls in a room. To investigate the fire behaviour of CLT panels, three full scale room tests were carried out in which the percentage of exposed CLT surface area was varied. The goal was to find the maximum percentage of unprotected CLT wall surface area that in case of a fire would result in self-extinguishment.

Another objective of this study is to improve an existing 1-dimensional numerical heat transfer computer model for CLT floors by incorporating an option of a CLT wall design. This tool will provide the ability to quickly determine the size for CLT floors and walls and their performance in fire. Ultimately, through the use of theoretical as well as experimental data, this study will provide a better understanding of CLT's behaviour in fire and develop knowledge regarding this relatively new product.

1.3 Scope of Work

Combustible building construction has been limited in height, number of storeys and floor area by the National Building Code of Canada [**2**]. These restrictions are based on a perceived higher risk of fire spread, added fuel to the fire as well as concerns for life safety and property damage. Many of these concerns come about the misconception that buildings constructed using light frame constructions behave similar to heavy timber construction such as CLT in a fire.

Previous research studied the behaviour of fully protected and fully unprotected CLT panels in a compartment [**3**]. This thesis aims to determine the optimal configuration of unprotected and protected CLT walls in a compartment that provides similar results to a compartment constructed using non-combustible material.

2 LITERATURE REVIEW

This chapter provides a summary of the literature referenced in this thesis. It includes previous research on CLT, such as material properties and fire performance. It also highlights the different methods for calculating the strength and fire resistance rating of various wood assemblies.

2.1 Cross-Laminated Timber

Cross-Laminated Timber is one of many heavy timber structural products being developed and used today. Other heavy timber products being developed include Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL) and many others having their own specific advantage. CLT was first introduced in the mid 1990's in Austria and Germany and its production has been growing ever since, CLT was introduced in North America in the early 2000s after realizing its potential from the experience in Europe [**4**]

CLT panels are comprised of a multi-layer wooden panel system. Each layer in the system consists of wooden boards positioned and glued perpendicular to each other. The advantage of this system is that it minimizes the impact of natural defects found in lumber and increases the overall compression strength and moment capacity by placing the outer layers parallel to the load. By gluing the layers of lumber in a perpendicular manner, it creates a uniform material that is stronger and more rigid than the individual lumber panels used to create it. CLT panels are manufactured with an odd number of layers; usually 3, 5 or 7 layers. The thickness of each individual board can vary from 10 mm to 50 mm and width from 60 mm to 240 mm [**4**]. The boards are finger joined, stress-rated and kiln dried. This method of construction allows for manufacturing of boards as high as 18 m and as thick as 400 mm which corresponds to massive structural elements. Figure 2-1shows the massive CLT panels that can be manufactured.

Figure 2-1: Seven-Ply Cross-Laminated Timber Planks [5]

Common species of timber used in manufacturing CLT panels include spruce, larch, pine, and firs. In general, softwoods are more common in manufacturing CLT but in certain circumstances hardwoods like poplar can also be used. One of the many manufacturing advantages of CLT is that layers with grains oriented parallel to the load provide the majority of the strength; this allows for lower grade timber to be used for interior layers and higher grade timber used for the outer layer. The material flexibility of configuration allows for more economical designs of floor systems where bending moment represents the critical load factor.

2.2 Manufacturing Process

The first step in manufacturing CLT members is the drying of the lumber used. Lumber is kiln dried to about 12% moisture content to prevent future shrinking or cracking in the final product. Each individual member is then cut to its proper width and length in correspondence to the specified design. Once all the individual lumber components have been cut to suit, boards are finger jointed using structural adhesive. The member is then pressed vertically and horizontally using a vacuum or a compressed air press. Finally the member is planned, sanded and openings are made using Computing Numerical Controlled (CNC) routing. CNC machining allows high precision cutting. As previously mention the final walls/floor sections could be as high as 18 m and as thick as 400 mm.

2.3 Strength of CLT

One of the greatest advantages of using CLT as the main structural component of a building is its ability to withstand loads. The cross-wise design of CLT panels allows for axial and compression strength in both orientation as well as adequate resistance to outer plane loading. In order to meet the code requirements for fire resistance the panels have to be built much thicker than what is needed to satisfy the structural requirements of the design. This causes the design to be structurally “overdesign” in many occasions considering that the building might never be exposed to fire conditions. Figure 2-2 shows the Bio Energy Facility building located in the University of British Columbia. This facility is an example of the many uses of CLT panels. The building uses CLT panels for the construction of walls and roof members.

Figure 2-2: University of BC Bio Energy Facility during construction using CLT panels [5]

In general, it is very difficult to determine with a high level of accuracy the mechanical properties of CLT due to differences in manufacturing process, species combinations, board orientations and overall design of the members. The CLT handbook [**4**] identifies that an experimental approach to determine these properties would yield accurate results but recognizes the high cost of testing multiple manufacturing parameters, layouts and wood species associated with it. The use of analytical procedures helps mitigate these experimental costs. By using educated approximations together with conservative assumptions it is possible to predict the mechanical properties of CLT and how it will behave out on the field.

2.4 Building with CLT

Building with CLT has many advantages both environmentally as well as economically. A good example of a CLT structure is the Stadthous building [**6**], a nine-storey building located in London's east end. Unfortunately, no fire studies were found for this building. Environmentally, the CLT structure eliminates the Carbon Dioxide that would have been generated if the structure were to be constructed out of steel or concrete. In addition trees keep greenhouse gases out of the atmosphere by storing them while growing. The building was estimated to save 300 tonnes of carbon emission which is the projected production of the building over a 21 year span [**6**]. Economically, these panels are prefabricated at the manufacturing facility which allows for a faster construction time at the job site. The lesser weight of the material in comparison to concrete allows for huge savings on the depth of foundations, transportation cost, as well as the elimination of a tower crane on the job site. This type of construction does not require curing time and is also less work intensive as the connections of floor and wall panels are simple. This contributes to huge overall constructions saving as is the case in the Stadthous building were total construction took 49 weeks from a previously estimated 72 weeks for the concrete building [**6**].

2.5 Combustible vs Non-combustible Construction

The National Building Code of Canada (NBCC) [**2**]divides buildings into separate categories based on type of occupancy, building height, as well as combustible and non-combustible construction. The NBCC, clause 3.1.4.1(2), states that any material with a flame spread rating greater than 500 is considered to be combustible. In accordance to clause 3.1.5.1 a non-combustible building requires to be built using non-combustible materials with few exceptions such as paint, fire stop material, roofing, glazing, flooring and wood paneling not thicker than 25 mm and with at flame spread rating equal or less than 150 (3.1.5.10).

2.6 Fire Safety

Fire safety is the intent to decrease the probability of an injury to a person in or outside the affected building as an immediate result of the design and construction of such[**2**]. In addition to the safety of occupants, fire safety also includes property protection, business continuity, as well as environmental protection by reducing the production of fire by-products such as toxic gases. These targets can be achieved by ensuring that occupants have adequate egress time, preventing fire spread through passive and active fire protection systems, and by providing adequate access to the fire department. Although the potential for losses is never completely eliminated, the use of proper fire protection techniques will contribute to a lower risk for human injuries and deaths [**7**].

Quantifying fire safety is very difficult task. What might be considered safe for a particular setup might not be safe in another application. An exact procedure or method to determine the fire safety of a building does not exist. As the Fire Protection Handbook [**8**] states , “There is no well-defined method of assessing life safety from fire in buildings. Life safety is a concept, and no formula can identify or guarantee that a building is safe from fire”. A computer model being developed at Carleton University called CUrisk aims at calculating fire risk and expected loses from fires in buildings [**9**]. This model has been used to evaluate the risk from fire in combustible midrise buildings [**9**].

2.7 Fire Risk

The objectives of the National Building Code [**2**] are found in Division A, Part 2 and the functional statements are found in Division A, Part 3. The applicable construction Articles are 3.2.2.50 for Group D (business and personal services occupancies), Up to 6 Storeys, Unsprinklered, 3.2.2.52 for Group D, Up to 4 Storeys, Combustible Construction, Sprinklered, and 3.2.2.49, Group D, Unlimited Height. The following risks must be evaluated for all of these construction types.

- Risk of fire spread beyond point of origin.
- Risk of occupants not able to evacuate the building.
- Risk of firefighters not able to conduct effective firefighting operations.
- Risk of fire spread to neighbouring buildings.
- Risk of fire spread beyond the compartment of fire origin.
- Risk of building collapse due to fire

A building of combustible construction must perform better or equal to a non-combustible building on the previous points in order to meet the NBCC objectives and functional statements.

2.8 Fire Resistance

Fire resistance is determined by "a measure of the ability of a building element to resist a fire" [**10**]. This resistance is usually measured as the time an element can meet a number of criteria during exposure to a standard fire resistance test [**10**]. The standard fires used during these tests include:

- ISO 834 - International standard used by many countries [**11**]
- ASTM E119 - US standard [**12**]
- ULC-S101 (ULC, 1989) - Canadian standard similar to ASTM E119 [**13**]

In buildings, limiting the fire spread and smoke movement to other compartments is accomplished by maintaining the integrity of structural and non-structural members that serve as fire barriers. Fire resistance allows occupants to evacuate safely, and firefighters to intervene and put out the fire by avoiding premature collapse. An assembly with a high fire resistance is able to contain the fire to a compartment preventing further property damage and ultimately the collapse of the building. Fire resistance becomes vital in high buildings where egress times are longer, and in buildings where people have difficulties moving such as retirement homes, hospitals, theaters, etc.

2.9 Fire Resistance Rating

Fire resistance rating is defined by the NBCC as "the time in minutes or hours that a material or assembly of materials will withstand the passage of flame and the transmission of heat when exposed to fire" [**2**]. This resistance times are measured in laboratory tests under specified conditions. The fire resistance rating test differs according to the assembly tested. Horizontal building assemblies such as roofs and floors are placed in a furnace and are exposed to flames from the bottom surface. A number of specified loads are placed at the top as well displacement probes to measure the deflection of the assembly. Vertical building assemblies such as partitions or load bearing walls that are required to have a fire-resistance rating must be rated equally from both sides as fire could develop from either side [**14**]. Exterior walls require to be tested for fire rating from the inside of the building as the compartment fire is expected to be more severe and likely than a fire starting in the exterior of the building [**14**]. In Canada, these tests are performed under the ULC-S101 standard fire.

There are three criteria that are evaluated when determining the fire resistance rating of an assembly [**4**].

- *Structural Resistance*: The assembly should withstand the applied load throughout the duration of the fire.
- *Integrity*: The assembly must prevent the passage of flames, gases or smoke hot enough to ignite a cotton pad on the unexposed side.
- *Insulation*: The temperature on the un-exposed side of the assembly must not increase by more than an average of 140°C or more than 180°C at any particular location.

The time at which any of these criteria is no longer met, determines the fire resistance rating of the assembly. Often, fire-resistance ratings are given in hours or parts of hours for comparison with requirements in building codes. For example, a wall tested to have a 65-minutes fire resistance will usually be assigned a fire resistance rating of one hour.

2.10 Ignition of Cross-Laminated Timber

Cross-Laminated Timber is considered a heavy timber product. CLT requires large energy inputs in order to increase its surface temperature which is essential for ignition. Much of the energy required to rise the temperature of the wood is dissipated into the thick panel. Heavy timber sections such as CLT panels can absorb a large amount of energy because of their greater mass.

The section factor is the ratio of the heated perimeter to the area of the cross section [**10**] and itplays a significant role on the time of ignition of a material. The rate of heat input is directly proportional to the section factor, therefore a greater perimeter to surface area ratio allows for more rapid heating of a particular section. CLT panels have large cross section areas which results in a low section factor and consequently low heat input. A lower heat input allows for a prolonged heating time before ignition.

2.11 Charring Rate of Cross-Laminated Timber.

During a fire, the surface temperature of the wood rises until it reaches about 300°C when it starts to char. The accepted theoretical value of charring temperature of wood used in North America is 288°C [**10**]. Before wood reaches this temperature, at about 200°C, it starts to undergo a process called pyrolysis which is the thermal decomposition of the wood into combustible gases. These gases serve as the fuel that burns while the black layer that is left behind is called char.

When heavy timber is exposed to fire, the surface of the wood burns rapidly until a char layer develops. As more wood burns, the char layer increases in thickness and acts as thermal insulation to the wood immediately underneath it. As the thickness of the char layer develops, the initial burning rate decreases to a slower steady rate. The constant charring rate for hardwoods is about 0.5 mm/min and about 0.65-0.75 mm/min for softwoods [**10**]. Figure 2-3 shows the different stages along a wood section from ambient temperature to pyrolysis and finally to char.

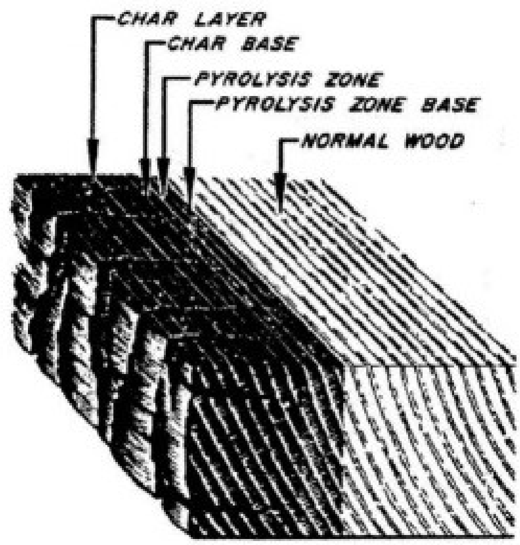

Figure 2-3: Char layer and pyrolysis zone in timber beam [10]

Although every wood species will char at a slightly different rate due to water content, humidity, species and density, overall the 0.65 mm/min serves as an acceptable charring rate for quick hand calculations [**15**]. Knowing the rate of charring is critical for engineers and designers as it allows them to determine the remaining unaffected cross-section of wood that is still available to support the load at different times throughout the fire. The time at which the minimum cross section area of the wood required to support the load is reached defines the fire resistance rating.

The charring rate and charring depth of CLT are more difficult to determine than solid sawn timber. The reason behind this lays on their physical differences in composition and makeup. As explained earlier, CLT consists of multiple layers glued together to form a massive structural component. Studies on some CLT panels have shown that thermoplastic adhesives such as polyurethane which are used to hold the CLT layers together fail at a temperature of about 200°C [**16**]. Early CLT layer falloff, called delamination, causes an increase in the intensity of fire and charring rate due to the fresh and newly exposed wood underneath the affected layer. If the layers that make up the panels can remain together, the charring rate of CLT can be assumed to behave similarly to the charring rate of solid sawn lumber.

2.12 Temperature Below Char Layer.

During the study of CLT and other wood products under fire, it is assumed that wood that has experienced complete pyrolysis and thus has become char possesses zero strength. Similarly wood located immediately underneath the char layer experiences reduced strength properties [**4**]. The temperature gradient through the CLT cross section helps determine when the adhesive and therefore the CLT layer will fail. It also allows to monitor what portion of the cross-section is remains at ambient temperature. After multiple experiments, equations have been developed to predict the temperature below the char layer at any specified location [**10**]. During tests, other methods must be employed to determine the position of the char layer such as the average and instantaneous charring rates which will be explained during the results section of this report.

2.12.1 Theoretical

Knowing the temperature below the char layers allows designers to determine the distance from the char at which the adhesive will fail. Eurocode 5 provides an equation, explained by Buchanan [**10**] to calculate the temperature at certain distance “x” away from the char onset. Equation (1) shows the temperature below the char layer. T_i represents the initial temperature of the wood; T_p is the temperature at which charring starts, around (300°C); *x* is the distance below the char layer; and *a* is the thickness of the heat affected layer, about 35 mm. It is recognized that there is no change in temperature when *x* reaches the value of *a*. Wood located at a depth greater than *a* from the end of the char layer is considered to be at the initial temperature T_i.

$$T = T_i + (T_p - T_i)\left(1 - \frac{x}{a}\right)^2 \tag{1}$$

2.13 Zero Strength Zone

The layer immediately underneath the char layer undergoing pyrolysis is called the heated zone or zero strength zone. This, along with the char depth, accounts for the two most important factors in determining the remaining strength of the wood. At the beginning of fire exposure, the heated zone is considered to be almost zero. As the fire progresses, the heated zone increases linearly up until it reaches a constant depth underneath the char base. This depth could vary depending on the fire exposure duration, type of assembly or section, as well as the type of heavy timber product. For example, the CAN/CSA O86 suggests that for built up glulam wood members such as beams and columns, Equation (2) is adequate to estimate the thickness of the heated zone for fires less than 20 minutes and Equation (3) for fires longer than 20 minutes. For this particular equation, 7 mm is the equilibrium thickness and it occurs when the fire exposure reaches 20 minutes.

$$x_t = \left(\frac{t}{20min}\right) \times 7mm \qquad \text{(for t } < \text{ 20min)} \tag{2}$$

$$x_t = 7mm \qquad \text{(for t } \geq \text{ 20min)} \tag{3}$$

Where t corresponds to time of exposure in minutes and x_t represents the thickness of the heated zone in millimetres

For CLT the equilibrium thickness that is recommended for design calculations is 10.5 mm for floor slabs experiencing tension on the bottom fibres, and 15.9 for walls experiencing compression on the side of exposure [**4**]. A similar relation to Equation (2) and (3) can be used to estimate the thickness of the heated zone through the first 20 minutes of exposure. Equations (4), (5), (6), and (7) can be used to calculate the thickness of the heated zone in a CLT wall or floor assembly. In this equation, x_t represents distance in millimeters from the base of the char layer and t stands the fire exposure time in minutes.

<u>CLT Floor Slabs</u>

$$x_t = \left(\frac{t}{20min}\right) \times 10.5mm \qquad (\text{for t} < 20\text{min}) \tag{4}$$

$$x_t = 10.5mm \qquad (\text{for t} \geq 20\text{min}) \tag{5}$$

<u>CLT Wall Assembly</u>

$$x_t = \left(\frac{t}{20min}\right) \times 15.9mm \qquad (\text{for t} < 20\text{min}) \tag{6}$$

$$x_t = 15.9mm \qquad (\text{for t} \geq 20\text{min}) \tag{7}$$

2.14 Effects of Fire Exposure on the Mechanical Properties of Cross-Laminated Timber.

The strength of wood sections could vary depending on multiple factors. Mechanical properties of wood could differ depending on wood grain orientation, type of load (compression or tension) as well as load duration. The Wood Design Manual [**17**] provides the strength characteristics of different species of wood in shear, tension, compression and bending strength at ambient temperature. There is a limited amount of information however, on the properties of wood at elevated temperatures.

Moisture Content plays a big part on the mechanical properties of CLT during fire. As the wood heats up, water in wood starts to evaporate. Some of this water vapour starts to be driven out of the wood. The other part is driven into the wood which improves the fire resistance of the member but also softens it decreasing its moment capacity [**10**]. Depending on the dimensions of the specimen and the test set up, there may be variations from the expected theoretical strength values. Plasticity of wood also increases as it heats up, reducing the tensile and bending moment of members [**10**]. Without the increase in plasticity cracks would form on the outer most tension fibres of the wood creating sudden failure. Instead, wood will fail plastically, redistributing the stresses to the unexposed and cooler fibres of the member [**10**].

2.14.1 Modulus of elasticity

The modulus of elasticity is an essential parameter on many wood strength calculations such as compression strength, tensile strength, bending moment capacity as well shear strength. Results from Nyman [**18**], Schaffer [**19**], Preusser [**20**] and others show how the modulus of elasticity decreases linearly up to 200°C [**10**]. Figure 2-4 and Figure 2-5 display the percentage decrease of the modulus of elasticity of wood as temperature increases.

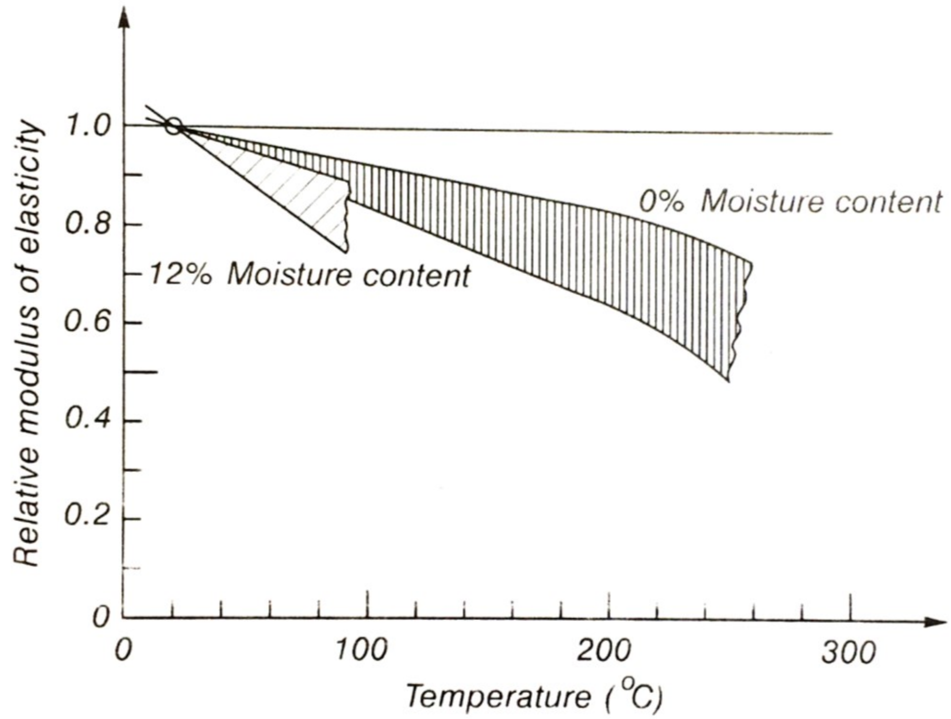

Figure 2-4: Modulus of elasticity of wood parallel to the grain versus temperature [10]

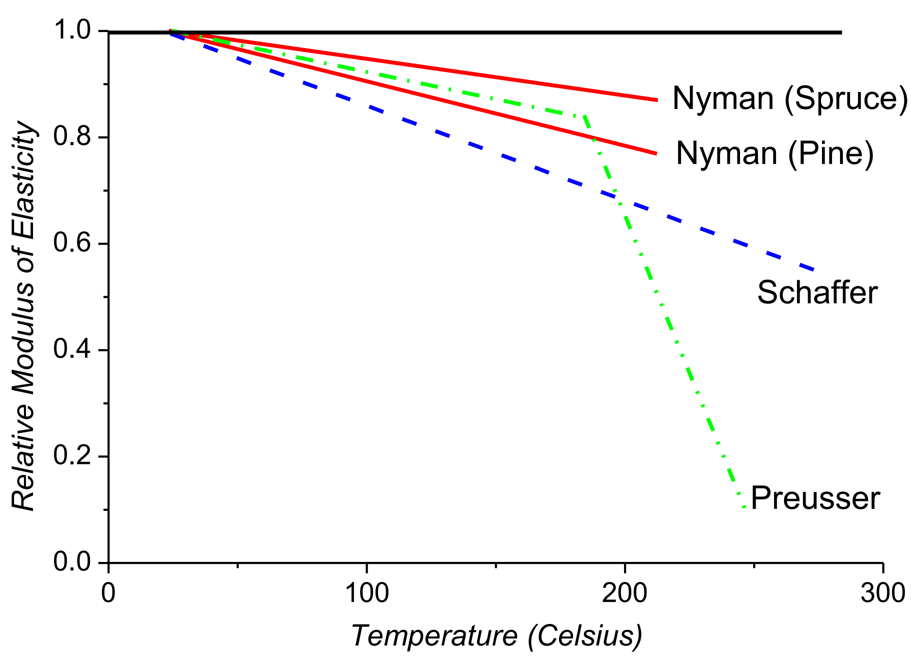

Figure 2-5: Modulus of elasticity of wood parallel to the grain versus temperature. Adapted from Gerhards [21]

2.14.2 Tensile strength

The tensile strength parallel to the grain of wood and CLT decreases as temperature increases. Figure 2-6 shows the variance in tensile strength of samples of spruce tested at 90°C and 25°C and with moisture content of 29.5% and 2.5%. These tests conducted by Ostman [**22**] show that an increase in moisture content has a negative effect on tensile strength. Test at elevated temperatures were performed by Lau and Barrett [**23**] who tested specimens that were preheated at 250°C for 25 minutes. The specimens experienced brittle failure at stress levels lower than the stress of the same specimen at room temperature.

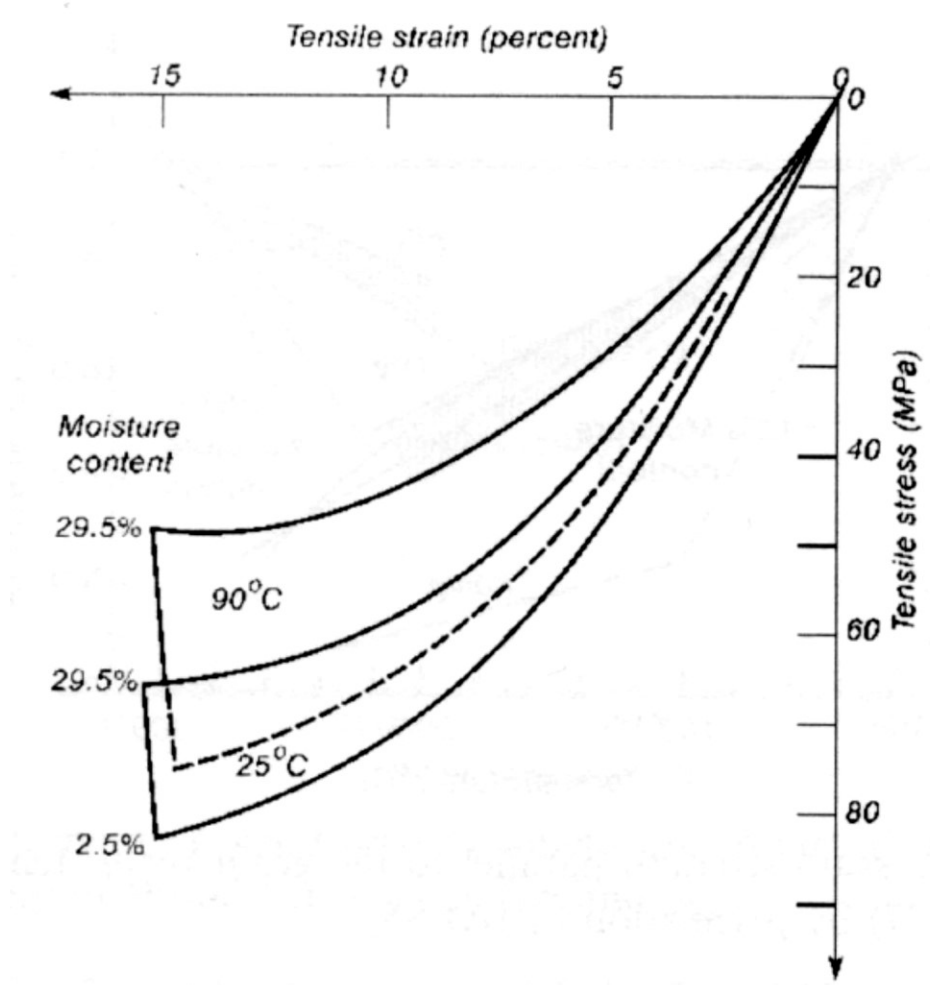

Figure 2-6: Stress-Strain relationships for wood in tension parallel to the grain [10]

2.14.3 Compressive strength

Similarly to the behaviour experienced in tension, wood's compressive strength decreases when heated up. The decrease is more evident for wood with high moisture contents (M.C > 12%). Figure 2-7 shows that woods with high moisture content will lose about 75% of their compressive strength at 100°C. Relatively dry wood will perform better only loosing 20% of its compressive strength at room temperature when expose to 100°C.

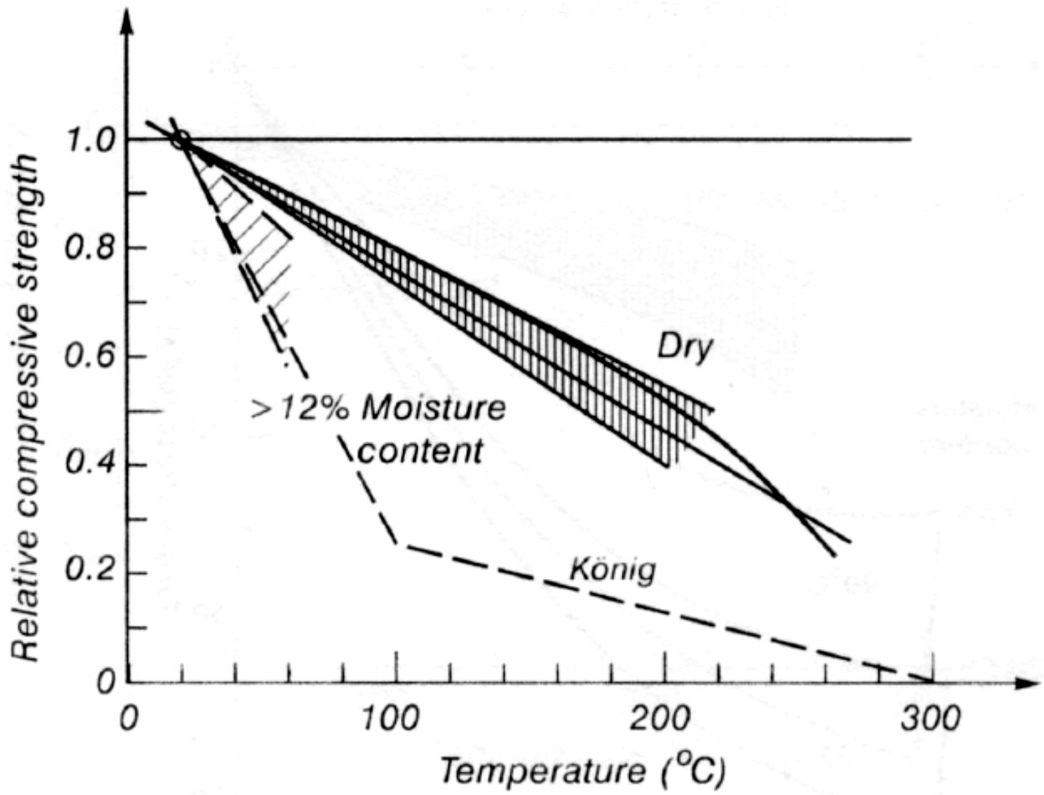

Figure 2-7: Compression strength parallel to the grain versus temperature [10**]**

2.14.4 Bending strength

The bending behaviour of wood at high temperatures can be described using its performance in tension and compression. Much like in compression, moisture content will have an impact on the type of failure and overall strength of the specimen [**10**]. Wood with high moisture content will be susceptible to plastic behaviour, causing large strains on the compression layer and overall large deformation. Figure 2-8 shows the reduction factor of the bending strength of wood when subjected to high temperatures from studies conducted by Glos [**24**] and Kordina [**25**]

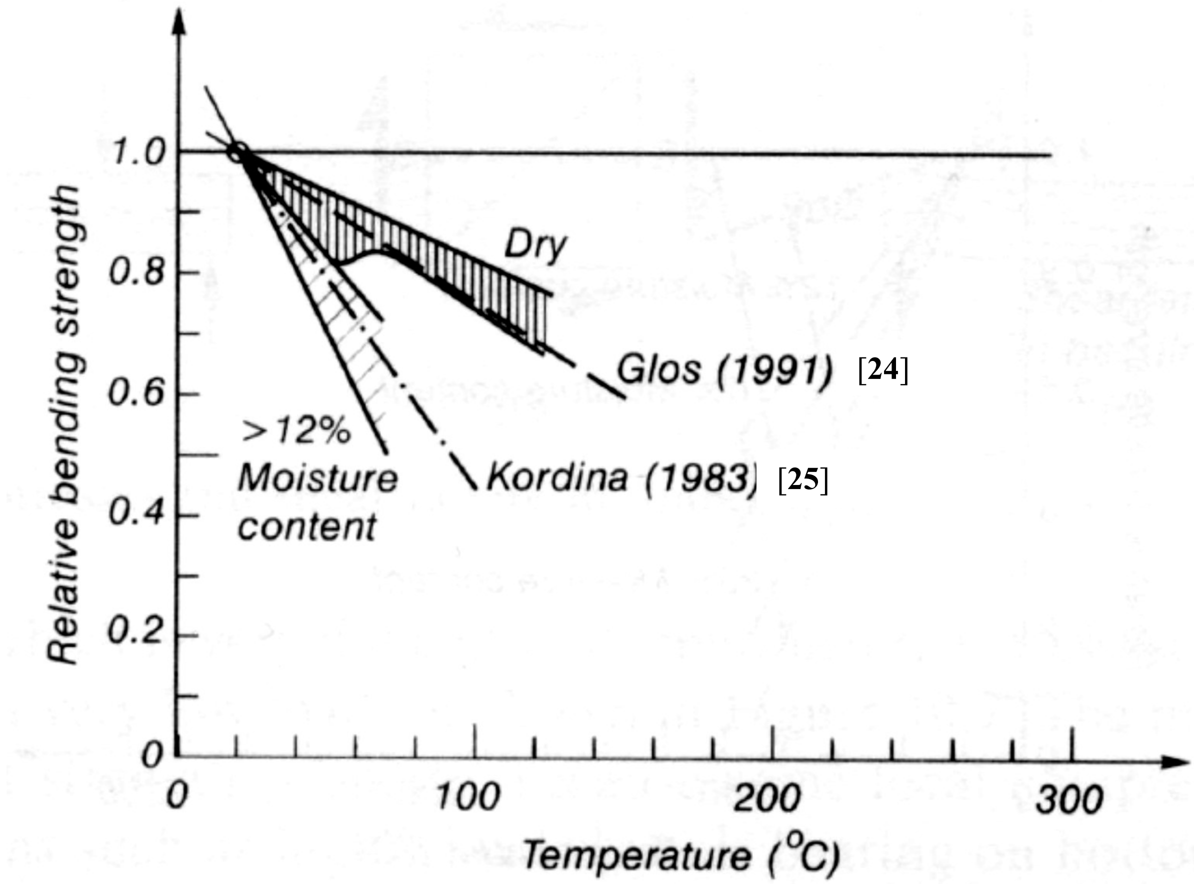

Figure 2-8: Bending strength of wood versus temperature [10]

2.15 Effects of Adhesives Properties on the Fire Resistance of CLT

Two common glues used in the manufacturing of CLT are polyurethane and melamine urea formaldehyde [**26**]. Trial testing concluded that the performance of polyurethane was inadequate during a fire as the member's layers fell off during testing before charring fully. Melamine urea formaldehyde remained intact throughout the test [**27**].

Another study was performed recently in which phenol-resorcinol formaldehyde, polyvinyl acetate and polyurethane were tested for their ability to support the charred member during a fire [**16**]. The test concluded that the phenol-resorcinol formaldehyde CLT samples showed no signs of delamination, whereas 60% of the polyvinyl acetate CLT samples delaminated and all of the polyurethane CLT samples delaminated. From this study, it was concluded that the optimum adhesive for manufacturing CLT panels is phenol-resorcinol formaldehyde, as it had similar performance to that of solid timber in supporting the charring layer during fire exposure. The CLT panels used for the construction of the three rooms were manufactured using polyurethane glue to adhere the multiple plies. Polyurethane is the most common adhesive used in the industry because of its relative lower cost and workability as compare to other adhesives.

2.16 CLT Fire Protection Alternatives

The use of protection systems can increase the fire resistance rating of CLT panels or any other heavy timber product. By delaying the onset of the charring process, the cross section of the CLT panels is able to remain intact for a longer period of time. The increase protection allows engineers to choose panels of smaller cross-sections in their design, knowing that the wood will remain at ambient temperature and therefore maintain its strength properties.

There are multiple alternatives used to protect CLT from direct fire exposure. The most common method of protecting exposed CLT assemblies is the use of gypsum board. Gypsum is readably available, easy to install by contractors and also poses a high specific heat capacity due to its chemically bonded water [**28**]. Other passive protection systems include the use of intumescent paints. Pressure driven fire retardants are also used, but they may have a negative effect on the strength of the wood [**17**]. Active and effective fire protection systems are sprinklers which can be used in combustible and non-combustible construction.

2.16.1 Gypsum Boards

Gypsum board is a widely available product found as the main facade material in the interior of most residential homes. Its ease of fabrication and relatively low cost makes it a very popular choice. Gypsum boards are made up of gypsum plaster pressed together between two layers of paper. Gypsum boards are commonly found in most home improvement retail stores in thickness of 1/2 inch as well as 5/8 inch, although other thicknesses are available. Panels are 48-inch and 54-inch wide with standard lengths of 8, 10, and 12 feet.

Gypsum plaster ($CaSO_4 \cdot 2\ H_2O$) is the main component of the board's inner core. Other substances can be introduced to increase certain properties such as fire resistance, moisture resistant, and reduction of sound transmission. Gypsum is not combustible and does not conduct heat easily. Gypsum contains roughly 21% of water. This allows it to perform extremely well under high temperatures. Water possesses a high specific heat capacity, which means that it takes a lot of energy to increase its temperature. This energy absorption, gives gypsum boards the desired superior fire performance that makes it a great insulator. As the temperature of the gypsum reaches 100°C, water starts to be driven off, causing shrinkage of the material. While the water is driven off the temperature levels off at 100°C and remains there until all the water has evaporated [**28**]. The shrinkage of the gypsum board is the primary cause of failure as the connections with the screws weaken and cracks form.

There are multiple types of gypsum boards available, each possessing unique properties. Type X gypsum board is preferred for fire protection. Type X gypsum board is designed to resist shrinkage when exposed to high temperatures allowing it to remain in place for longer periods of time [**29**]. Fire experiments revealed the fire resistance rating for different types and thickness of gypsum board when used to protect heavy timber panels such as CLT [**30**] [**3**]. The CAN/CSA

O86 standard [**17**] recommends the following failure times for gypsum boards attached to heavy timber panels.

- (a) 15 min for 1 layer of 12.7mm (1/2 in) Type X gypsum board
- (b) 30 min for 1 layer of 15.9mm (5/8 in) Type X gypsum board
- (c) 60 min for 2 layers of 15.9mm (5/8 in) Type X gypsum board

2.16.2 Intumescent and fire retardant coatings

A new form of protecting structures against fire is the use of intumescent paint. This type of cover is designed to expand in volume in the presence of extreme heat. This foam-like expansion, serves as an insulator to the structure protecting it from direct flames. Intumescent coats where originally created to be applied on steel structures which lose their strength at high temperatures, but have started to be applied on wood structures. Research is currently being conducted to gain a proper understanding of the properties of this relatively new product [**31**].

2.17 Assemblies' Fire Resistance Calculations

Heavy timber structures exposed to fire char at a constant rate. The charring rate of the wood can be used to determine the remaining strength of a beam/wall/floor at any time during a fire. There are multiple methods to calculate the fire resistance of a heavy timber assembly. The type of assembly in question influences what type of method is better suited to calculate the fire resistance. The reduced cross-section and reduced properties method are the two most used calculation methods for determining the fire resistance of a beam/wall/floor. There are benefits and drawbacks to each calculation method as described below.

2.17.1 T.T Lie Equations

The T.T Lie equations were developed to calculate the fire resistance of laminated timber beams and columns in the 1970's and for over 20 years served as the only code-accepted design method for calculating the fire resistance of exposed wood members [**32**]. The T.T Lie equations present a semi-empirical method for calculating the fire resistance of timber beams and columns. It was originally developed as a way to quickly assess the fire resistance before proceeding to more involved calculation methods. Equations (8), (9), (10), and (11) were theoretically derived from studies by Imaizumi 1962 and Ödeen 1970 as well as from experimental tests on beams and columns [**33**]

The T.T Lie method is the predecessor of what is now known as the reduced property method. This method assumes a charring rate of 0.6 mm/min for wooden beams and columns. Also, there is a reduction to strength properties of 0.8 regardless of the member. This value was chosen to be on the conservative side as corner rounding of beams and columns is not explicitly considered. Fire resistance can be calculated as follows for 3 and 4-sided exposures.

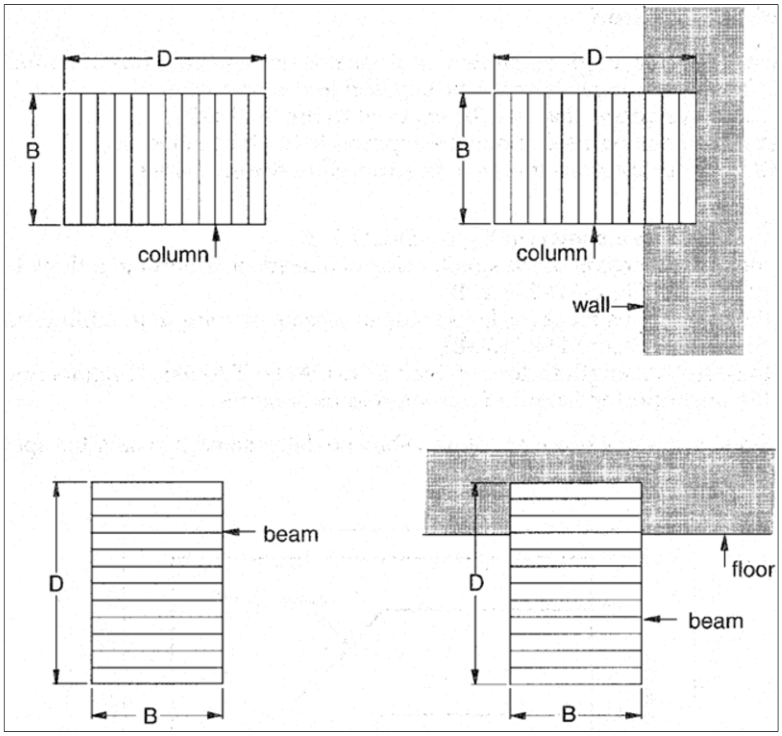

Figure 2-9: T.T Lie timber beams and columns nomenclature [34]

$$t_{FR} = 0.1fB\left[4 - \left(\frac{B}{D}\right)\right] \quad for\ beam\ exposed\ on\ 3\ sides \tag{8}$$

$$t_{FR} = 0.1fB\left[4 - 2\left(\frac{B}{D}\right)\right] \quad for\ beam\ exposed\ on\ 4\ sides \tag{9}$$

$$t_{FR} = 0.1fB\left[3 - \left(\frac{B}{2D}\right)\right] \quad for\ columns\ exposed\ on\ 3\ sides \tag{10}$$

$$t_{FR} = 0.1fB\left[3 - \left(\frac{B}{D}\right)\right] \quad for\ columns\ exposed\ on\ 4\ sides \tag{11}$$

Where:

t_{FR} = fire resistance rating (min)

f = load factor, which depends on the load and effective length on columns. Found in Figure 2-10

B = the full dimension of the smaller side of the section before the fire (mm). See Figure 2-9

D = the full dimension of the smaller side of the section before the fire (mm). See Figure 2-9

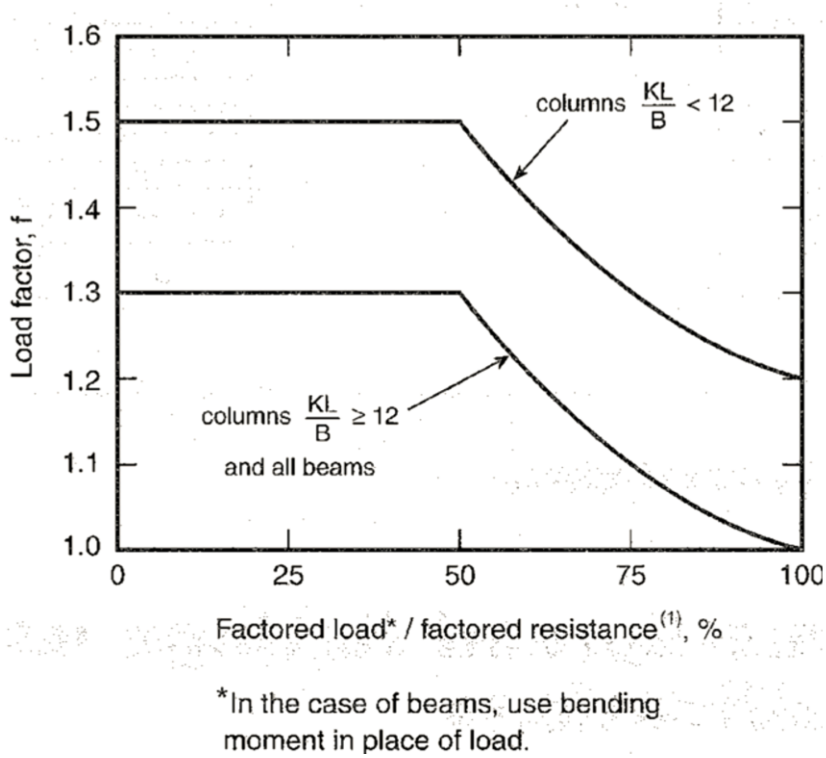

Figure 2-10: T.T Lie equation load factor [34]

2.17.2 Reduced Property Method

The reduced property method calculates the remaining cross section by removing the depth of the char layer [**34**]. To calculate the strength of a section, a reduction factor, less than one, is multiplied to the strength factor of the wood at ambient temperature. Equation 12 shows this relation where k_f is the reduction factor ($k_f < 1$) and f_b is the bending strength under normal conditions. In this case the reduction factor k_f depends on the size of the member. A significant drawback of the reduced property method is the inability to differentiate between smaller and larger cross-section areas. Wood assemblies with smaller cross-section heat up much faster than lager wood members. The reduced property method penalizes large cross section members as many of the strength properties of the wood at room temperature are factored down. Given that the reduction factor does not change as the cross-section becomes smaller, structures utilising large cross section members have the potential to be overdesigned.Figure 2-11 shows the reduction factor for the modulus of elasticity, tensile strength and compressive strength of wood as it heats up.

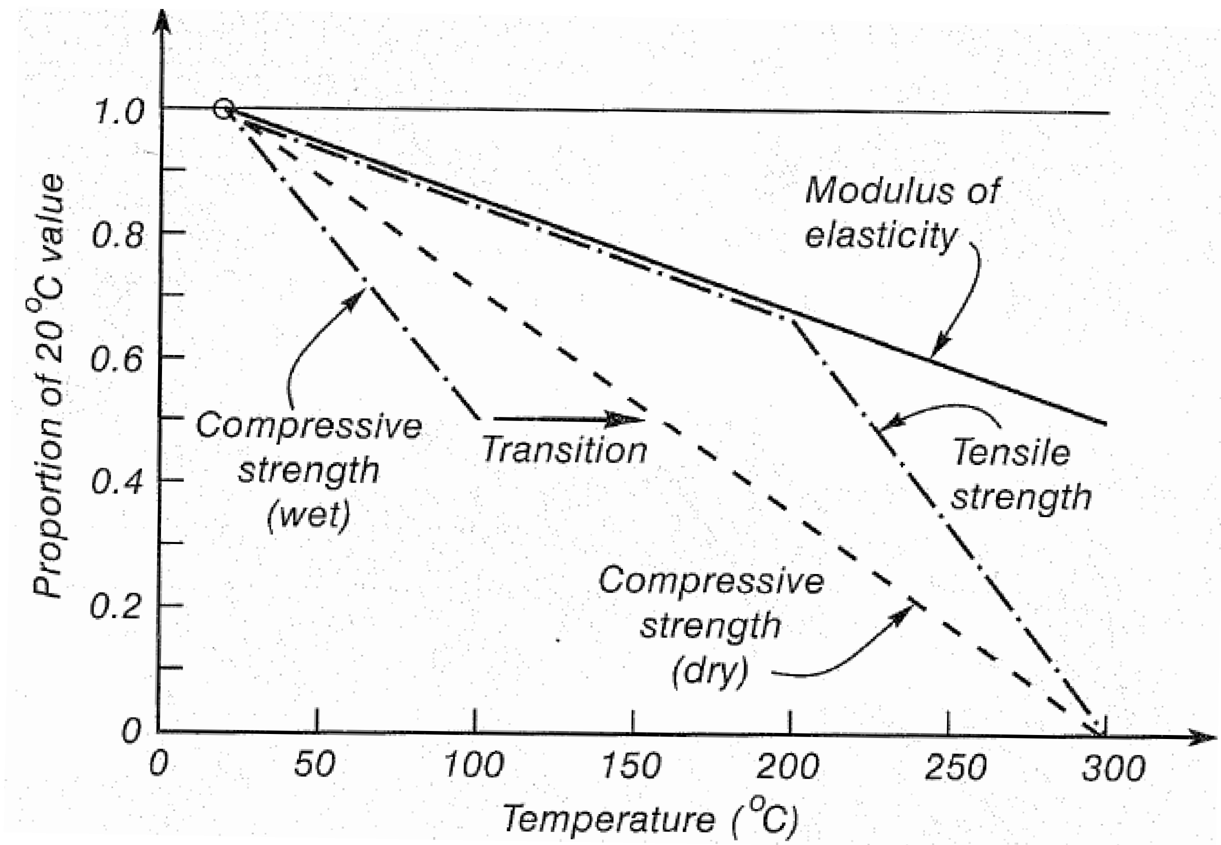

Figure 2-11: Effect of temperature on mechanical properties of wood [10]

$$f_f = k_f \times f_b \tag{12}$$

2.17.3 Reduce Cross-Section Method

The reduced or effective cross section method looks at the remaining cross-section at room temperature and calculates its strength. This method does not consider the depth of char and affected heated zone underneath the char for strength calculations. For the first 20 minutes of the fire, the char layer and heated zone will increase linearly until they reach equilibrium [**4**]. This method is preferred over the reduced property method since char and heated zone depth can be adjusted as time progresses. The reduced cross section method yields slightly conservative results since the reduced strength on the heated zone is completely ignored albeit its presence.

Figure 2-12 illustrates the charring behaviour of a timber beam exposed to fire. The three-sided exposure seen on the left is representative of a beam protected by the ceiling above. The four-sided exposure seen on the right is common on columns but also present in fully unprotected beams. Equation (13), (14), and (15) demonstrates how to calculate the effective width and depth of a timber beam or column that has charred.

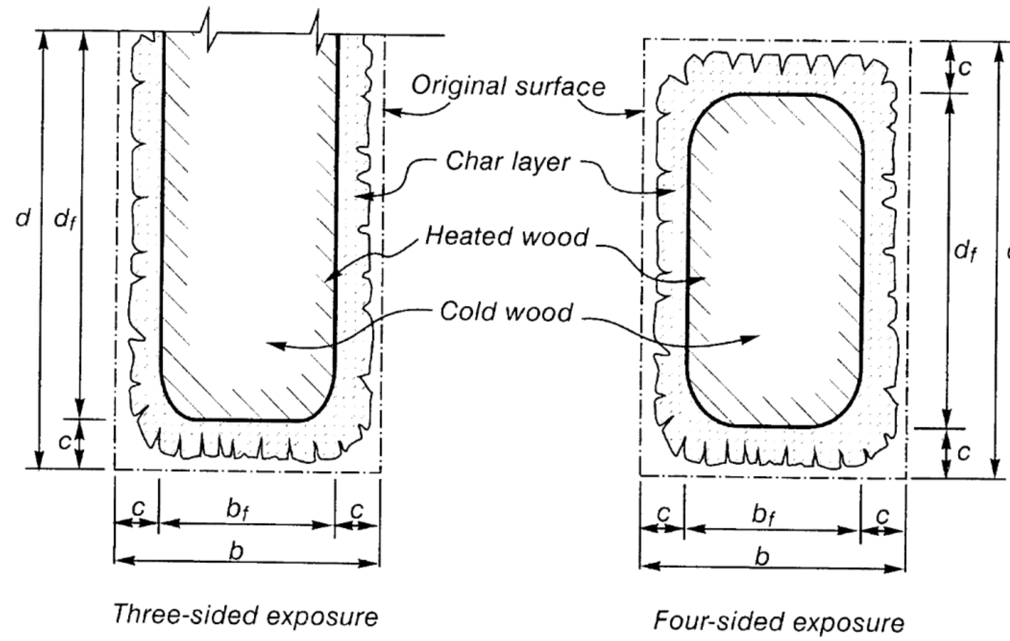

Figure 2-12: Char and heated zone depth for 3 and 4 side exposure [10]

$$b_f = b - 2c - d_h \tag{13}$$

$$d_f = d - c - d_h \quad \text{(new depth for three-sided exposure)} \tag{14}$$

$$d_f = d - 2c - 2d_h \quad \text{(new depth for four} - \text{sided exposure)} \tag{15}$$

The effective depth (d_f) and width (b_f) can be calculated using the calculated char depth, $c = \beta \times t$ where "t" represents time in minutes. The value of the charring rate of wood β commonly used is 0.65 mm/min. The 0.65 mm/min is an average value as charring rates are higher at the beginning of the burning period before the char layer is developed [**10**]. As the char layers starts to build up, it serves as an insulator therefore slowing down the rate of charring. The depth of the heated zone (h) varies with time of exposure and the size of effective cross-section remaining. Using these equations the effective area can be easily calculated as $A_f = b_f d_f$. Once the effective area is calculated for a particular time in the fire, the structural resistance of the assembly can be calculated using the Wood Design Manual [**35**].

2.18 Previous Room Tests

The room tests conducted as part of this research study follow a series of tests conducted by McGregor [**3**] who investigated the contribution of Cross Laminated Timber panels to a room fire. McGregor tested a total of five CLT rooms. The interior surface in some of the tests were fully protected with two layers of ½ inch type X gypsum board while in other tests all the surfaces were left unprotected. Some of the tests used propane and some used furniture as fuel. McGregor concluded that the CLT panels in the fully unprotected rooms contributed greatly to the Heat Release Rate and duration of the fire. The fully protected rooms had no contribution to the fire and self-extinguished once the furniture had been consumed. More details on the results of these tests are presented in the discussion section of this thesis.

3 ROOM FIRE TESTS

A number of room fire tests were carried out in the tunnel test facility of Carleton University's Fire Research Lab. The objective of these tests was to measure the temperature, heat release rate as well as the charring rate of the Cross Laminated Timber (CLT) panels that make up the walls, floor and ceiling of the test room. These tests are a continuation of a series of tests carried out by Cameron McGregor [**3**], who studied the contribution of the CLT panels to the fire development in a room with a single door opening. He looked at aspects such as fire growth, fire spread, panels charring depth, and total heat release rate and compared the behaviour of unprotected as well as fully protected CLT rooms using fire rated gypsum boards. The unprotected tests resulted in ultrafast fire growth with panel delamination. The delamination caused by failure of the interlayer adhesive allowed fresh wood to be exposed to the flames, causing re-ignition of the panels' interior layer. The fully protected tests performed by Cameron produced better results. During that test, the entire room content (furniture) was consumed without the involvement of the CLT wall panels in the fire.

His tests concluded that fully protected rooms were able to self-extinguish after the room contents were consumed. The tests involving no fire protection showed great contribution to the room fire from the bare CLT panels. Self-extinction was not achieved during these tests due to layer delamination caused by adhesive failure.

The tests carried out during this study complement Cameron's tests by considering fire development in CLT rooms that are partially protected by gypsum boards. The aim of these tests is to find an optimal configuration that provides maximum uncovered wood surface with minimum contribution of the CLT panels to the fire.

3.1 Setup of Tests Conducted

Three room fire tests were conducted during this study. The walls, the floor, and the ceiling of all three rooms were constructed using CLT panels. Each room had the same dimensions as well as fire load. Specific details regarding these tests are highlighted in the following sections.

3.2 Test Room

The test rooms were built on top of a platform constructed out of timber frame with a surface consisting of a 12.7 mm layer of Permabase cement board on top of a 12.7 mm layer of plywood.

All the walls, ceiling, and floor in the test rooms were built using 105 mm thick 3-ply CLT panels. The CLT panels for the first and second test were manufactured by Nordic Engineered Wood. The outer laminations were made out of Spruce-Pine-Fir (S-P-F) 1950Fb MSR 35x89 mm members and were oriented longitudinally. The inner lamination was made from S-P-F No 3/Stud 35x89 mm members with a transverse orientation. For the third test, Structurlam Innovative Wood Specialists supplied the CLT panels. The panels were classified as V2 by the manufacturer which corresponds to a No. 1/No. 2 S-P-F lumber for the plies with grades parallel to the load (outer layers) and No. 3 S-P-F lumber for the plies with grades perpendicular to the load (inner layer). The room interior dimensions are shown in Figure 3-1

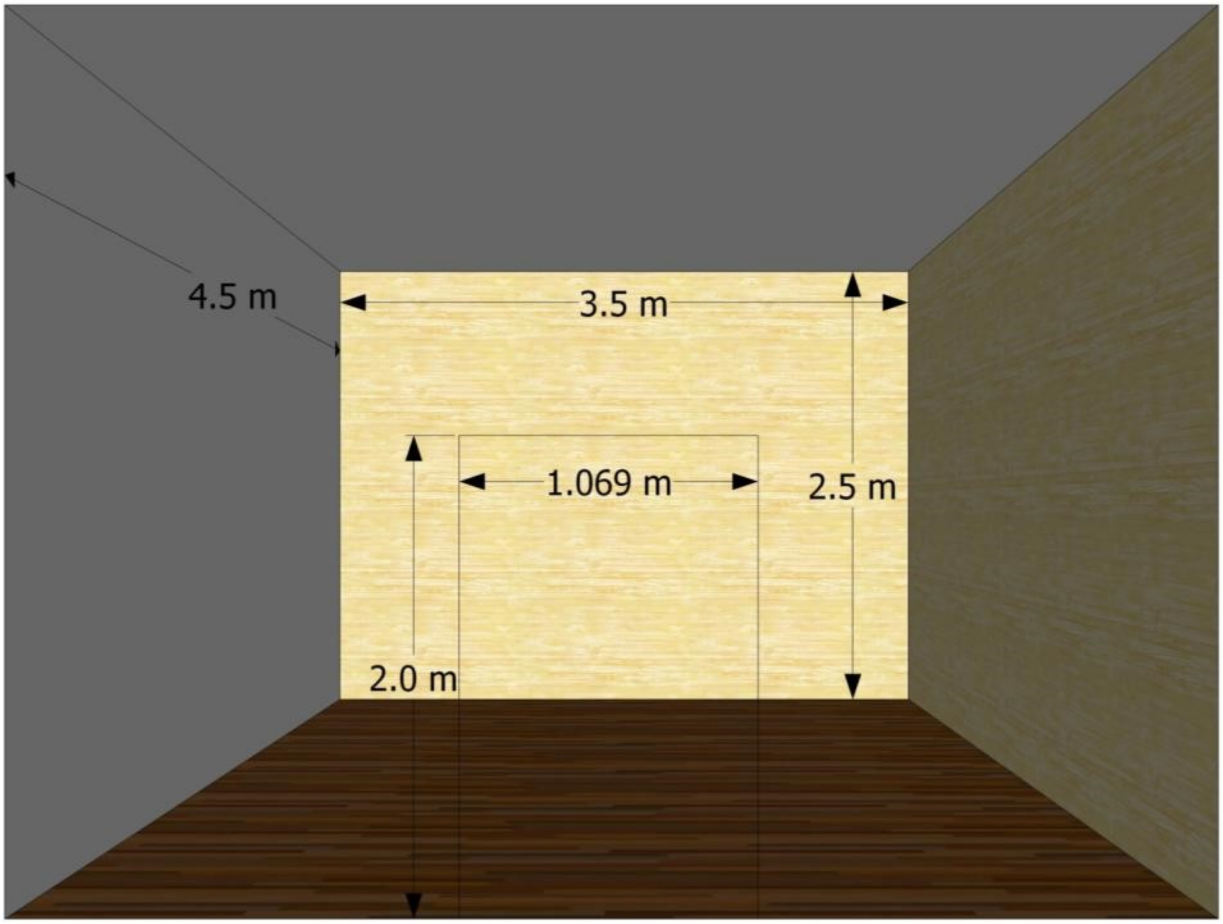

Figure 3-1: Room 1 interior dimensions

The set up for all three CLT room test conducted during this study is summarize in Table 3-1. The moisture content of every exposed CLT surface in the room was measured before the start of each test using Timber Check ™ moisture meter. The moisture content varied on each tests with drier panels in Test 1 which was conducted in the winter and higher moisture content in panels in Test 3 conducted in the summer. The moisture content value of each test is presented in Table 3-1

Table 3-1: Setup details for the three room fire tests

Test Number	**Test 1**	**Test 2**	**Test 3**
Date	Feb 11, 2013	May 09, 2013	July 04, 2013
Unprotected Wall Surfaces	Rear wall and Right wall as you enter the room	Right Wall and Left Wall as you enter the room	Right Wall as you enter the room
Gypsum Board Fire Protection	2 layers of ½ inch type X gypsum board		
Fire Load	Furniture and Clothes		
Thermocouple tree type	K- type thermocouples shielded by a steel tube and 1 inch Fibrefrax	K-type thermocouples attached to steel wire shielded with ½ inch thick Fibrefrax	K-type thermocouples attached to steel wire shielded with 1 inch thick Fibrefrax
Joints Sealed	YES	NO	YES
Ambient Temperature	-1 °C	19 °C	23 °C
Moisture Content of CLT Panels	8%	10.5%	13.5%

Figure 3-2 to Figure 3-5 illustrate the dimensions of the CLT panels used in the construction of the rooms.

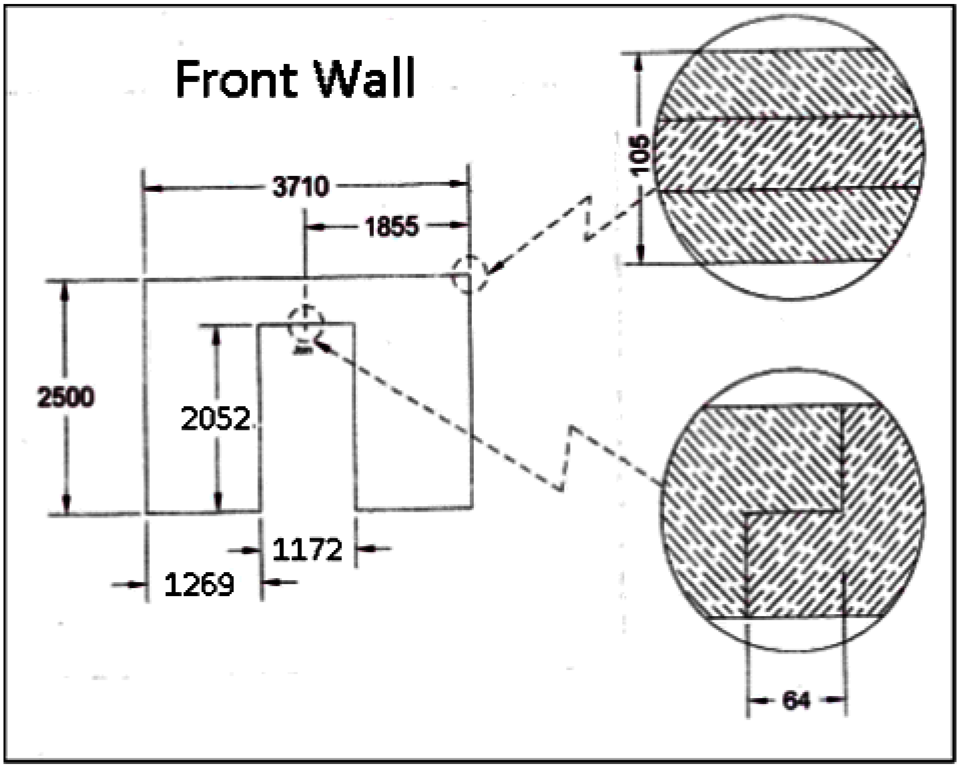

Figure 3-2: Dimensions in millimetres of front panels including the door opening

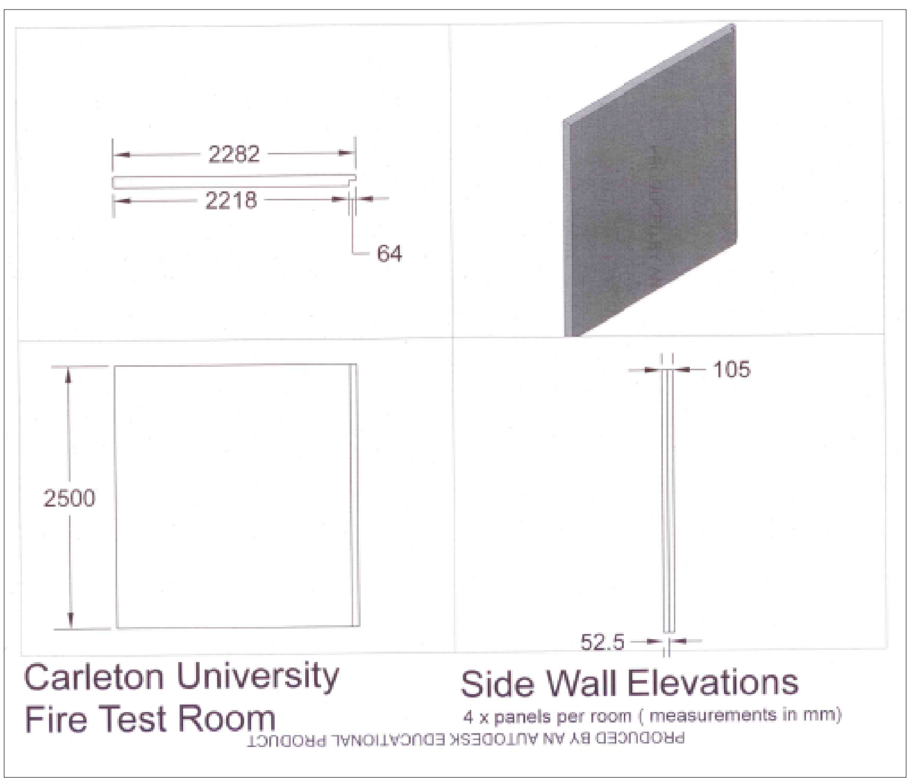

Figure 3-3: Panels used for the side walls of the room

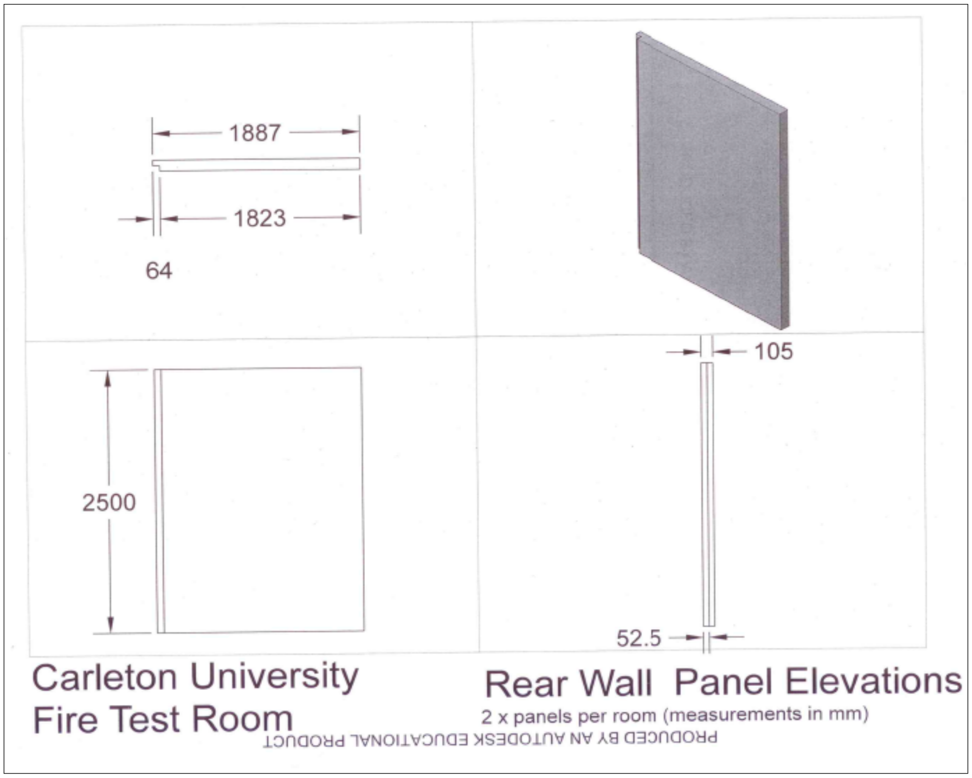

Figure 3-4: Panels used for the back wall of the room

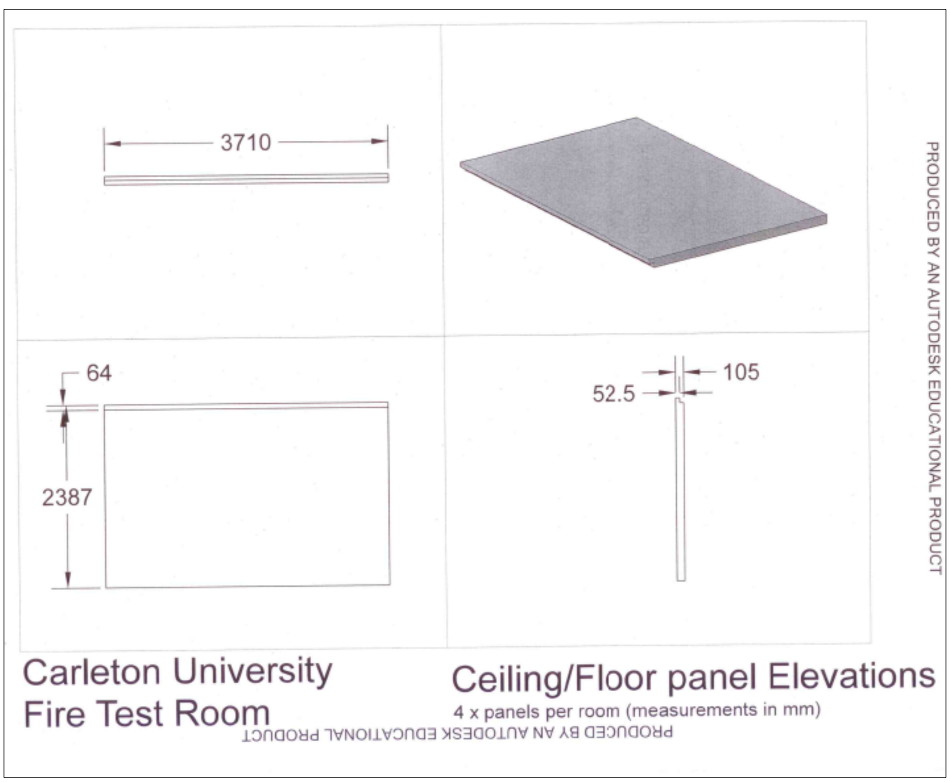

Figure 3-5: Panels used for the ceiling of the room

3.3 Panel Connections

Three types of joint connections were used to connect the CLT panels during the construction of the rooms. Each of the 4 walls of the room, as well as the ceiling and the floor were comprised of 2 CLT panels. To connect these panels to make a wall/ceiling/floor, lap joints were used. The end and edge distance and fasteners spacing is as specified by CSA O86 standard [**35**]. To ensure a perfect seal, fire caulking was used between the lap joints as well as between the wall and floor panels. A ¼ inch thick bead was applied in a zigzag motion along the entire joint using a caulking gun. This procedure is essential to prevent integrity failure.

To secure the lap joints, ø6 mm x 100 mm self-tapping screws were used at intervals of 300 mm. Figure 3-6 displays the cross section of a lap joint connection of a 5-ply panel. The figure is for illustration of the joint characteristics only as the rooms were constructed using 3-ply panels.

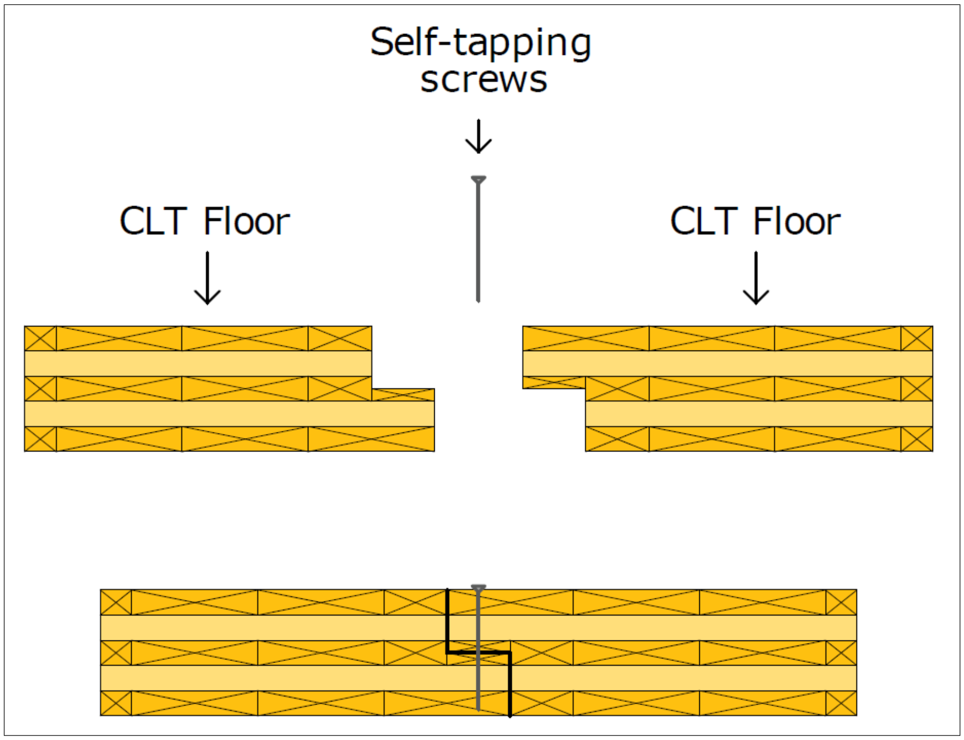

Figure 3-6: Cross section of lap join connection [4]

For wall-to-wall panel corner connections, ø8 mm x 180 mm self-tapping screws were used. This type of screw was also used to secure the ceiling panels to the top of the walls along the edge. The longer screw provided more rigidity to the connection and prevented joint separation. The screws were located at 300 mm intervals. Figure 3-7 represents this type of connection.

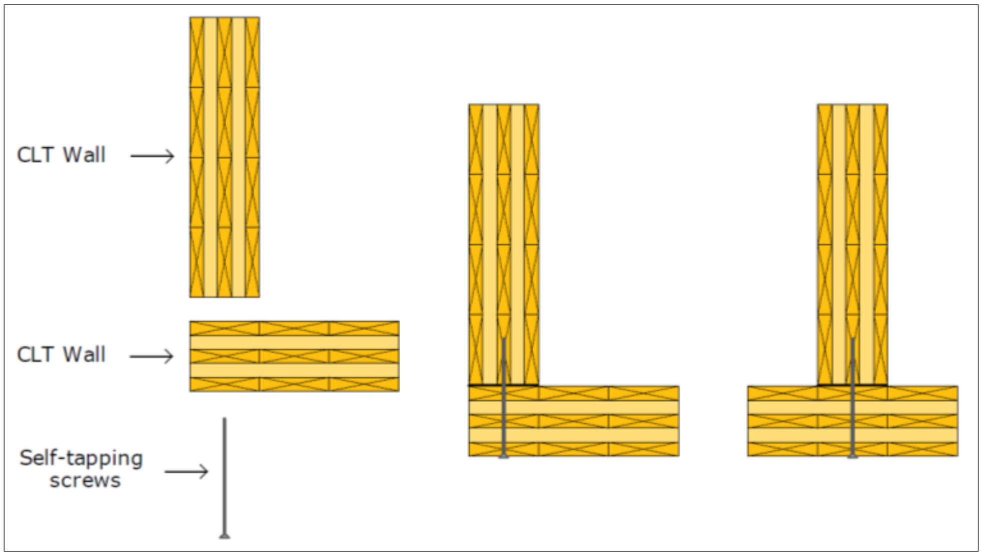

Figure 3-7: Wall-to-wall connection cross section [4]

For the floor/wall connection, ø8 mm x 180 mm self-tapping screws were used. The screws were driven at an angle of 45 degrees starting 64 mm from the top of the floor. The screws were drilled at 300 mm intervals. The 180 mm length of the screw was selected to provide a secure connection given the screws were introduced at an angle. Figure 3-8 shows an example of this type of connection.

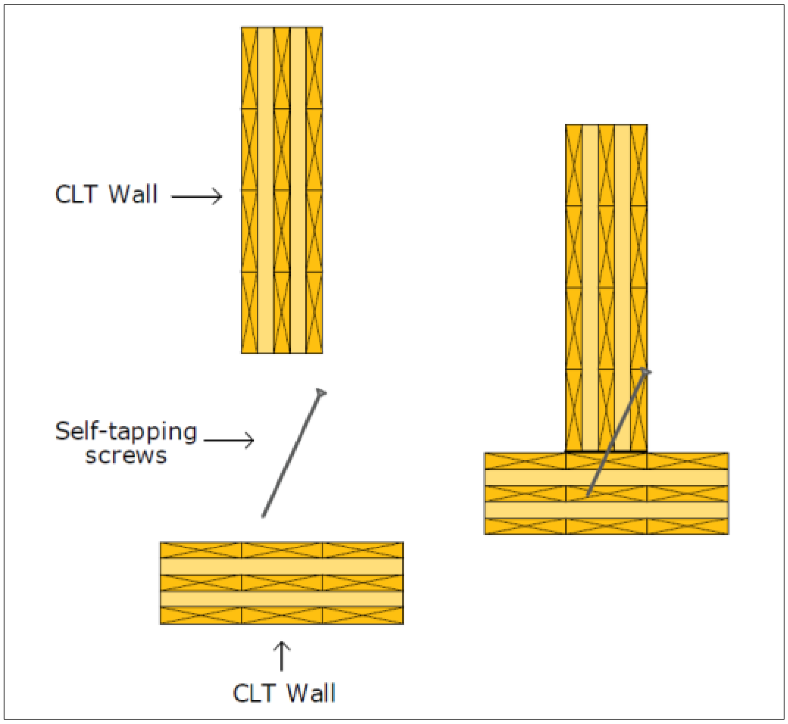

Figure 3-8: Wall-to-floor connection. Cross sectional view [4]

Given the nature of the material, wood is prone to having imperfections such as knots, warps and inconsistencies in the grain. The panels used for the test room had some imperfections such as cracks on the surface of the panels as shown in Figure 3-9. This was mainly due to non-uniform drying of the wood surface due to the low relative humidity present in the lab during the winter months. Other imperfections were due to shipping of the panels to the facility as well as the handling during the construction of the rooms. These minor defects could compromise the integrity of the first CLT ply and contribute to accelerated charring in the gaps and cracks

Figure 3-9: Panel imperfections due to uneven drying of the wood

3.4 Fire Protection

In order to protect the walls from impinging flames and direct heat, two layers of ½ inch type X gypsum boards were used on all predetermined protected surfaces of each of the three tests. To attach the gypsum boards to the CLT panels, drywall screws of different lengths for the first and second layer were used at a distance of one screw per foot in the vertical and horizontal direction. For the first layer, drywall screws with a length of 1-5/8 inches were used. Every drywall screw head was covered with plaster to protect it from thermal breaching. For the second layer, drywall screws with a length of 2 inches were used and every screw head was also covered with plaster. All the joints between the gypsum boards were taped and plastered to prevent passage of flames. The joints between the first and second layer of gypsum board were staggered to further protect from any passage of flames to the CLT panels.

To seal the floor-wall and the ceiling-wall joints from escaping gases, a silicon based fire rated sealant was used. To prevent damage to the CLT panels that formed the base of the room, a sub layer of non-combustible cement board was used. The cement boards were installed on top of the CLT floor panels and underneath the hardwood floor. The joints between the adjacent layers of cement board were sealed with the same silicon based fire rated sealant used on the wall, floor and ceiling joints.

The door opening of the room was also protected, in particular along the top half where flames were expected to exit during the test. Protecting the exterior of the room from burning ensures that the measured Heat Release Rate data is only from the fuel inside the room. Two layers of ½ inch type X gypsum board covered with a layer of 1 inch thick Fibrefrax ceramic insulation were used to cover the door frame as well as the entire exterior façade where the door opening was located. The covered room façade of Test 1 can be seen in Figure 3-10

Figure 3-10: Front View Fibrefrax protected façade and thermocouple trees during Test 1

3.5 Test Instrumentation

Data such as room and panel temperatures and heat release rate were collected during the 3 room fire tests. To properly determine the charring rate of the CLT, it is necessary to know the temperature of the panels at known depths. To measure the temperature at specific depths of the CLT, Omega type-k thermocouples were used. Holes were drilled from the exterior surface of the room to reach the pre-determined depths measured from the interior surface of the CLT panels. The thermocouples were then embedded with a tight fit into each respective hole. To measure the temperature of unprotected CLT panels, 6 thermocouples were embedded at different depths. Depending on the particular test, the unprotected wall surface of interest was equipped with 4 to 6 groups of 6 thermocouples each. To measure the temperature of protected CLT walls, a total of 3 thermocouples per group were used. Two groups of thermocouples were used for the protected CLT panels. Table 3-2 shows the depths of the embedded thermocouples in groups measuring protected as well as unprotected walls. Figure 3-11 shows a thermocouple group containing 6 embedded thermocouples. Figure 3-12 illustrates the 6 thermocouple groups measuring internal temperatures at different locations of the unprotected wall.

Table 3-2: Depth of Embedded Thermocouples

Thermocouple Groups of 6 or 3 thermocouples	*Depth from room interior of **thermocouple groups located on unprotected walls***	*Location of thermocouple in **walls protected with 2 layers of gypsum board***
Thermocouple 1	3 mm	At the interface between the two layers of gypsum board
Thermocouple 2	6 mm	At the interface between the CLT panel and the second layer of gypsum board
Thermocouple 3	9 mm	6 mm from the interior CLT surface into the wood
Thermocouple 4	12 mm	-
Thermocouple 5	18 mm	-
Thermocouple 6	24 mm	-

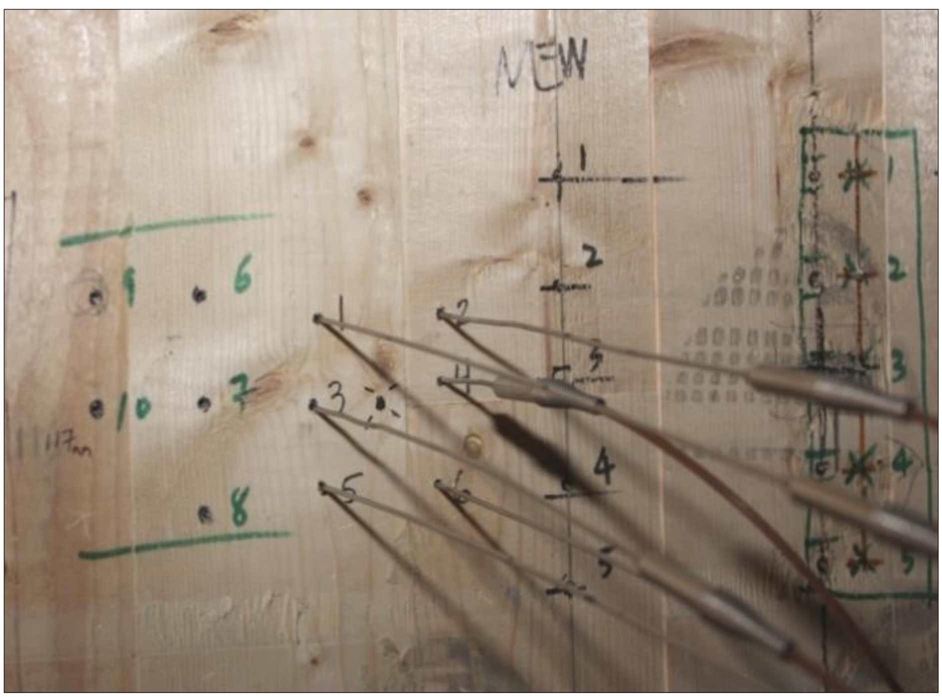

Figure 3-11: A thermocouple wall group containing 6 embedded thermocouples

Figure 3-12: Six thermocouple wall groups measuring the internal temperature of an unprotected wall

To measure the temperatures at different locations in the room, four thermocouple trees and a plate thermometer was used. For Test 1, each thermocouple tree was built using a steel rod. This was intended to shield the thermocouples from physical damage associated with the fall-off of gypsum from the ceiling. 5 mm diameter holes were drilled in the steel rod every 0.4 m starting from the floor of the room in order to accommodate the thermocouples. A total of 6 thermocouples were used per tree at locations of 0.4 m, 0.8 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m from the floor. For Test 2 and 3 the steel rod was omitted since gypsum falloffs from the ceiling did not affect the trees. The steel rods warped due to elevated temperatures during Test 1 and they could not be reused. Thermocouple trees for Test 2 and Test 3 were secured using an insulated thermocouple wire. The individual thermocouples were attached at the specified heights of 0.4 m, 0.8 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m from the floor similar to Test 1. A plan view showing the location of each thermocouple tree and the plate thermometer are shown in Figure 3-13.

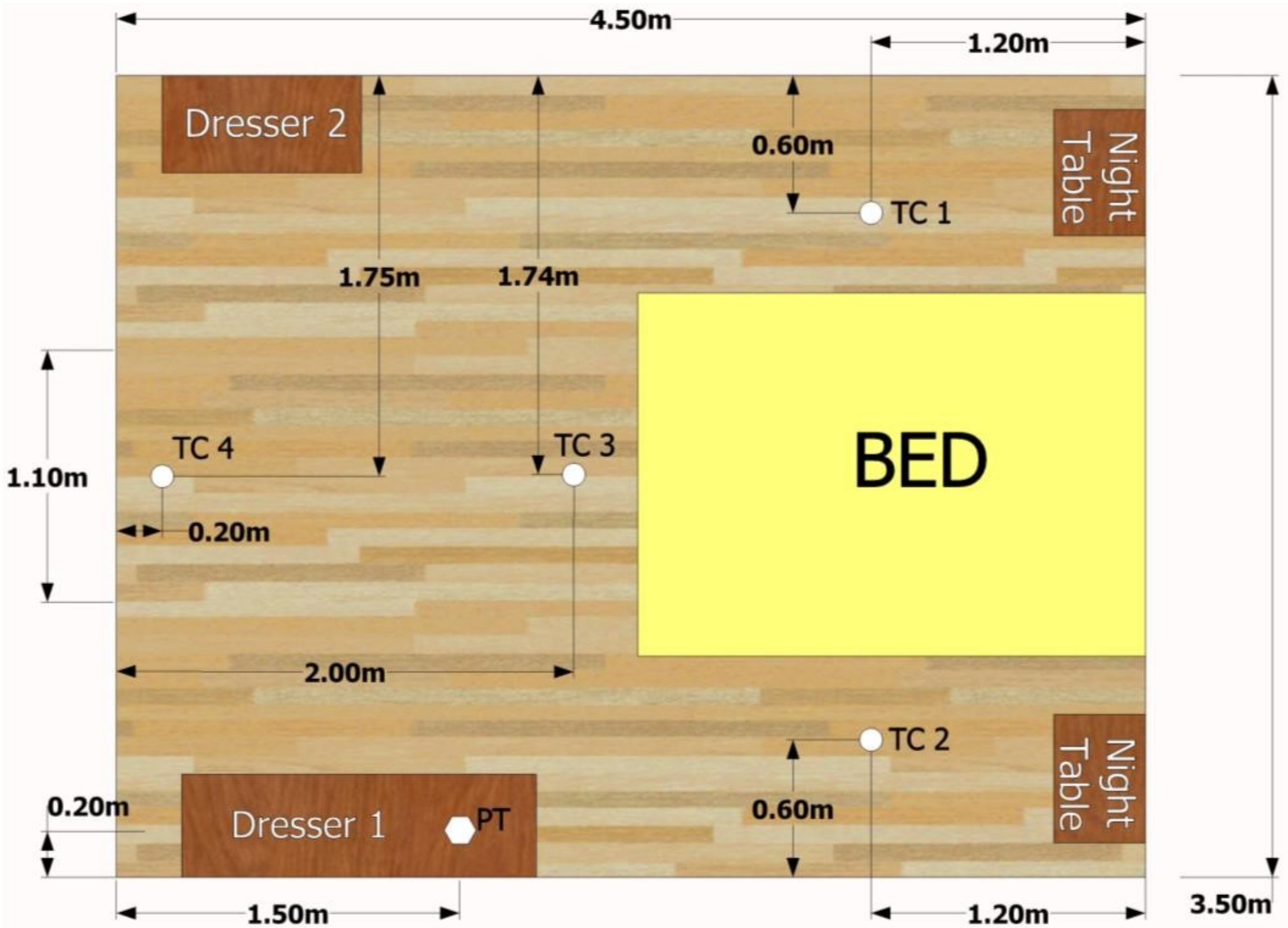

Figure 3-13: Location of four thermocouple trees and a plate thermometer

In order to protect the thermocouple trees installed to measure temperatures in the room, two different methods of protection were used. For the first test, the K-type thermocouple wires were protected using a steel tube covered with an inch thick Fibrefrax ceramic insulation. For the second and third test, a steel fire rated wire was used to attach the K-type thermocouples. For the second test, a ½ inch thick layer of Fibrefrax ceramic insulation was used while for the third test the thickness of the insulation was increased to 1 inch. The increase in the insulation thickness during Test 3 was to protect deformation and elongation of one of the trees, which occurred during Test 2. The support and wires of the plate thermometer were protected from high temperatures using an inch thick Fibrefrax insulation. Figure 3-14(a) shows the Fibrefrax insulation around one of the thermocouples of a thermocouple tree. Figure 3-14(b) shows the protected plate thermometer located 0.95m from the ceiling.

(a)

(b)

Figure 3-14: Thermocouple tree (a) and plate thermometer (b) protected with Fibrefrax fire insulation

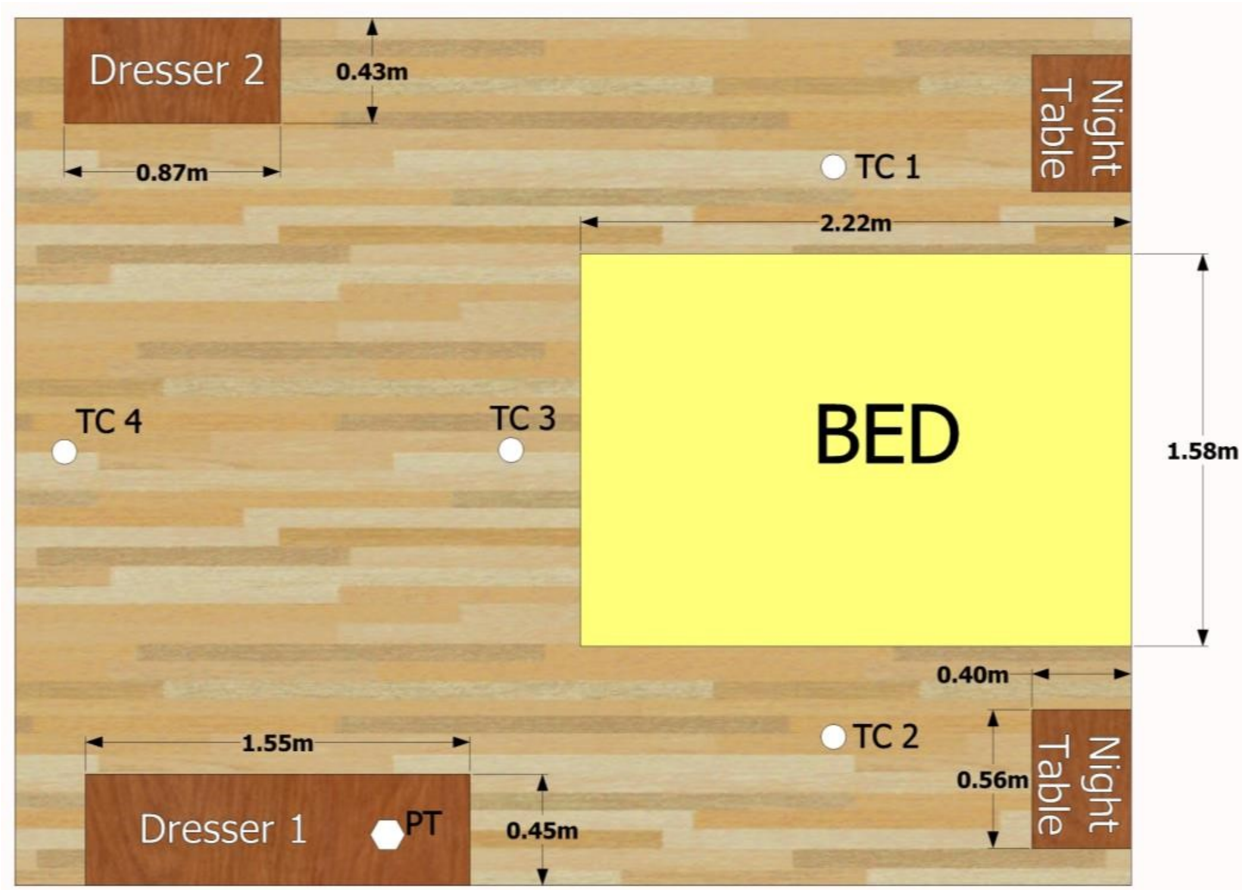

Figure 3-15: Furniture layout of the test room with dimensions in meters

The specific locations as well as dimensions of the furniture in the room are shown in Figure 3-15. Similar furniture and locations were used for all three tests. Figure 3-16 shows the bed with the two night tables and the two dressers in the room before the test.

Figure 3-16: Furniture set used in all three room tests.

3.6 Heat Release Rate Measurement System

In order to measure the contribution of the unprotected CLT panels and room content to the fire, the Heat Release Rate (HRR) produced by the fire was recorded throughout the test. To measure the HRR, all products of combustion leaving the room were drawn by three exhaust fans through a measurement chamber where oxygen, CO, and CO_2 concentrations as well as velocity and temperature were measured. This process of calculating heat release is known as the oxygen consumption calorimetry [36]. The principle is that at 25°C and 101.3 kPa the heat produced per unit mass of consumed oxygen is relatively constant at 13.1 MJ/kg of oxygen.

The full scale HRR measuring system at Carleton University tunnel test facility is capable of accurately measure up to 13 MW fires [37]. A calibration factor is required to adjust for an overestimation in flow rates from flow deflection near the chamber walls. The factor ranged from 0.83 to 0.85 for HRR's of 2.4 to 5.6 MW [38] [39]. The calibration factor is required to adjust for an overestimation in flow rates. Because of the distance (approximately 20 meters) separating the test room and the measurement devices in the chamber, there is a time delay in the HRR output. This delay is less noticeable in larger and longer lasting fires. Figure 3-17 illustrates the HRR measurement system present at the Carleton University tunnel laboratory.

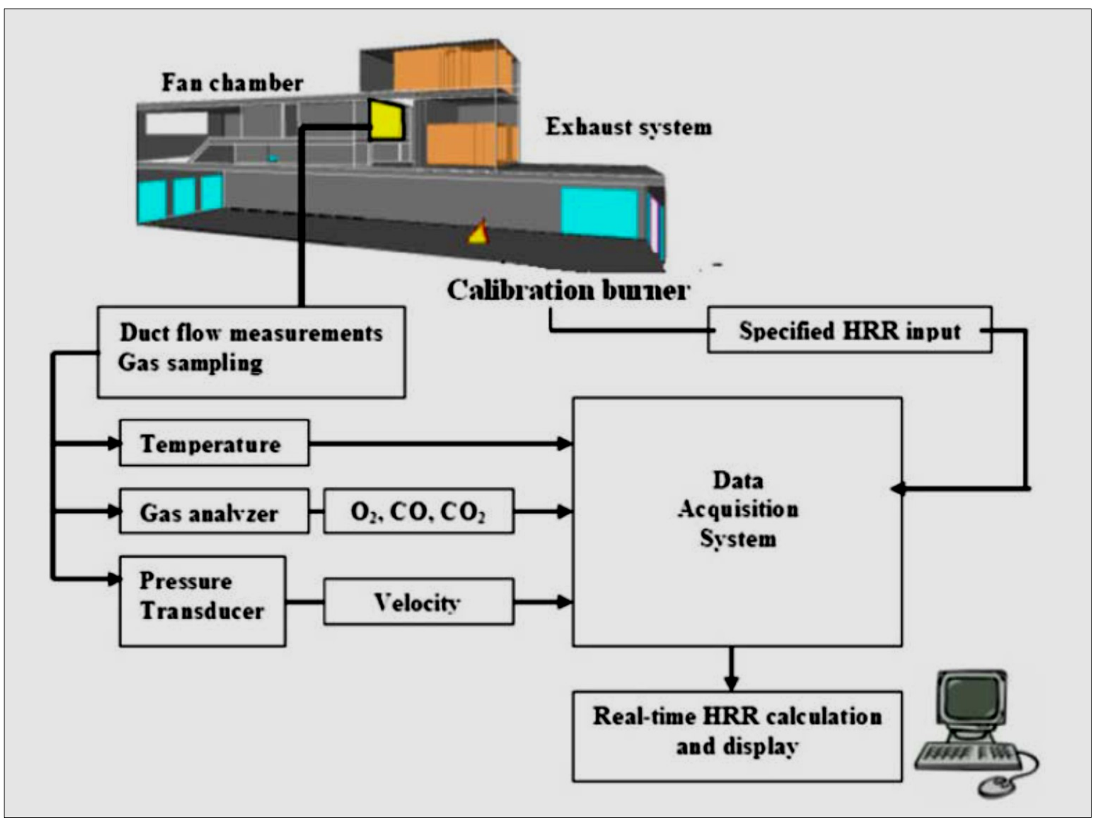

Figure 3-17: Schematic of Carleton University HRR measurement system [3]

3.7 Fuel Load

To achieve comparable results, the fuel load and fuel type were similar for all tests. This allowed us to determine the contribution of the exposed CLT panels to the room fire. The total mass of combustible content, not including the bare CLT walls, was about 455 kg, 223 kg of which was the hardwood floor. Table 3-3 details the specific net calorific value as well as the mass of all the combustible contents in the room.

Table 3-3: Total Fuel Load for the three tests.

	Net calorific value ΔH_c (MJ/kg)	Mass (kg)	Fuel Load Energy Density per m^2 floor area (MJ/m^2)
Head Board / Footboard	18	29.5	33.7
Mattress	20	37.0	47.0
Box spring	20	10.0	12.7
Dresser	18	46.0	52.6
Tallboy Dresser	18	59.0	67.4
Night tables	18	24.0	27.4
Clothes	20	20.0	25.4
Pillows	20	2.0	2.5
Sheets	20	2.0	3.0
Duvet	20	2.0	2.5
Hard Wood Floor	18	225.0	257.1
TOTAL FUEL LOAD			**531.6**

Although the hard wood floor of each test was composed of different wood species, their densities were relatively similar and floor thickness was the same. Each of the items was weighed at the laboratory and heat of combustion values used were based on a survey of Canadian residential buildings performed by Bwalya [**40**].

3.8 Room Construction Method

The CLT rooms were constructed using two steel cranes built with wheels. The cranes were used to lift and place the massive panels. The entrance panels were placed first followed by the right side wall panels and the left side wall panels. The room was completed by installing the two panels of the back wall and the two panels that make the ceiling. Fire caulking was used to seal the lap joints between panels.

The room was then lined with gypsum boards and the joints were sealed with plaster compound. The second layer of gypsum was then added ensuring that the joints from the first layer were staggered with the joints in the second layer. The hardwood floor was then added and the rooms were then furnished with two dressers, two night tables and a bed fully dressed. The exterior façade of the front wall were covered with Fibrefrax fire insulation to protect it from exiting flames during the tests.

3.9 Video Recording

To record the events of the room fire tests, 3 video cameras were used. Two stationary cameras; the first one recording from the front of the room and a second recording from the right side for a better shot of the exiting flames. A third camera was used by a technician to record important details and close-up shots. These videos were used to determine gypsum fall-off times, time of complete furniture consumption and other important test details.

4 RESULTS

Three room fire tests were carried out at Carleton University Fire Research Lab as part of this research study. The rooms had the same dimensions and door size and they were built out of 3-ply CLT panels, each layer having a thickness of 35 mm. Each room had a different configuration of protected surfaces. For Test 1, the right wall and rear wall of the room were left unprotected. For Test 2, the right wall and left wall were left unprotected. For Test 3, the right wall of the room was the only unprotected surface. The combustible contents were kept identical in all three room tests in order to provide a good comparison of room temperatures, heat release rate and charring rate of the CLT panels. The goal of these tests was to determine the maximum interior wall surface area that could be left unprotected and would result in self-extinguishment following the consumption of the room furniture. The ceiling of all three room tests was kept protected with 2 layers of ½ inch Type X gypsum board.

4.1 Test 1 – Unprotected Back Wall and Right Wall, All Other Interior Surfaces Covered

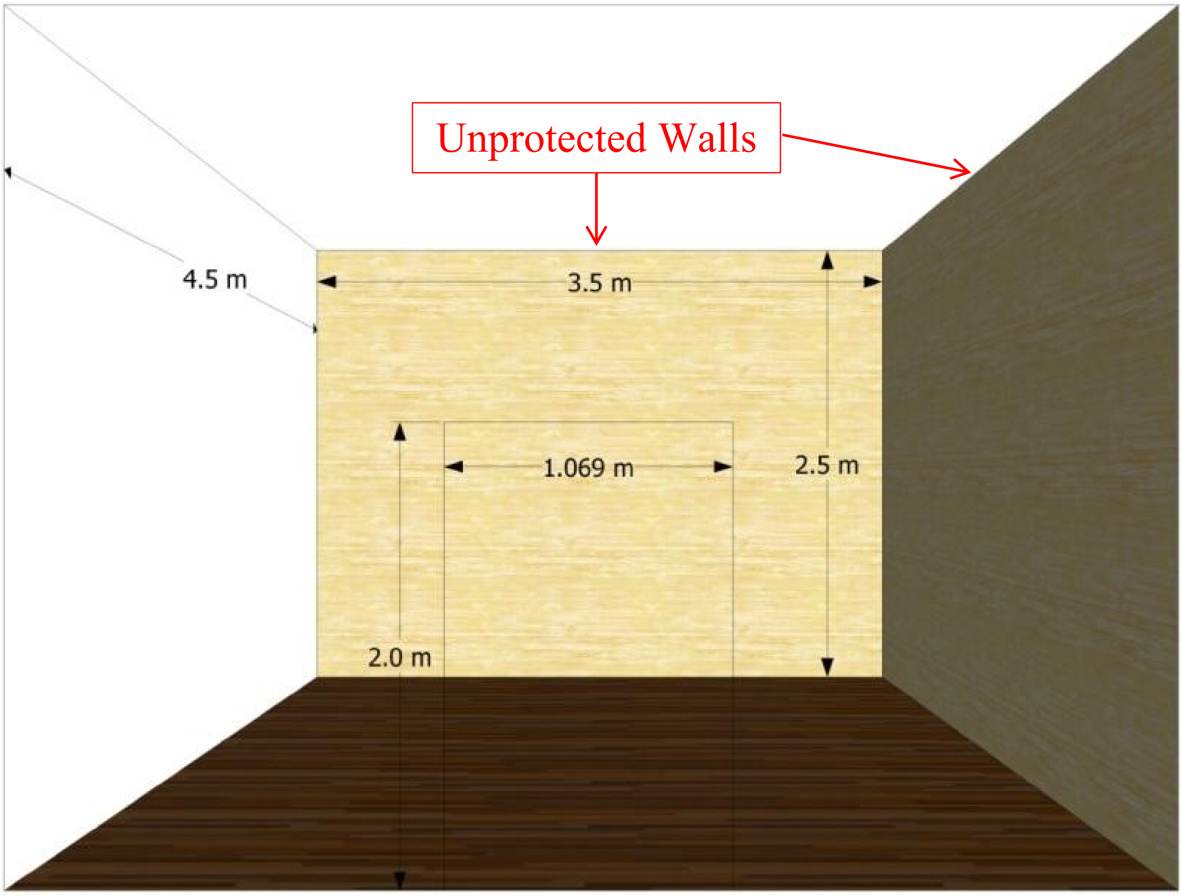

Figure 4-1: Sketch of Test 1 including interior room dimensions

Test 1 was conducted on the morning of February 11, 2013. The right wall and back wall were left unprotected. The two unprotected walls had a total surface area of 20 m^2 which accounted for 52.8% of the wall surface area in the room or 28.8% of total surface area of the room counting floor and ceiling.

4.1.1 Description of the test

The room was manually ignited by the lab technician using a propane burner at 11:22AM. The temperature of the room at the time of ignition was -1 °C. Throughout the length of the test all three exhaust fans in the facility were operating at 75% of their maximum capacity with a mass flow rate of about 140 kg/s.

The first ignited item in the room was the pillow located on the right side of the bed. Thirty seconds later, self-sustained burning was achieved and black smoke from the pillow started to accumulate at the ceiling, three minutes after ignition the fire spread to the entire bed, and from there it spread to the bed headboard and the night tables located at the back corners of the room. Temperatures in the room rose slowly for the first 4 minutes of the test. At around 11:26AM (4 minutes after ignition) the flames spread to the second night table and started impinging vigorously on the back-unprotected wall. The burning of these new items led to a noticeable increased in room temperature. By 11:27AM the temperature in the room had reached 400°C and still increasing very rapidly. The unprotected CLT walls started to become more involved in the room fire which caused temperatures to increase further. Flashover occurred about 5 minutes into the test. At this time the entire room contents became involved in the fire. By 11:41, almost 20 minutes from ignition time, the room temperature had reached 1200°C. Flames were vigorously escaping through the top of the door opening.

Figure 4-2: The lab technician ignites the propane burner used to ignite the first ignited item (pillow)

Figure 4-3: Self-sustained fire of pillow is obtained

The temperature in the room remained steady at about 1180°C until 11:46AM when most of the fuel associated with the furniture had been consumed. Room temperatures started decreasing slowly until they reached 350°C at around 12:30 PM, 68 minutes after initial ignition. During this period of decreasing temperature, the room interior surfaces became more visible as much of the smoke had dissipated. The gypsum board on the ceiling and the left side wall was still in place. The back wall and right-side wall were completely charred and the first ply was starting to delaminate at some locations.

Lower parts of the back wall, where the night tables were located, were still burning. This could be due to the residual of clothes stored on the drawers before the test as well as the remaining of the night tables. A small delamination of the first CLT ply occurred in the center at mid height of the back wall. This area was affected more severely at the beginning of the test due to its location directly above the bed. Another member delaminated mid height of the right side wall, about 2 meters from the door. A third delamination occurred at mid-height of the corner between the back and right-side wall. This was the largest of the three delaminations, exposing lots of fresh wood underneath.

Figure 4-4: Premature delamination leads to some flares

Figure 4-5: The right corner of the room reignites

Figure 4-6: The fire starts to gain strength, burning vigorously and flames start to impinge the ceiling

The fire started to regain strength once again as the newly exposed and fresh wood was becoming more available due to delamination. Delamination occurred due to failure of the adhesives holding the wood layers together. The wood adhesive used was Thermoplastic Polyurethane (PU) which has a melting point of 210 ^{o}C. At around 12:33 PM, 71 minutes after ignition, the temperature in the room started to rise once again. The temperature continued to rise as more pieces of CLT were delaminating. The room underwent a second flashover at about 12:37PM, 75 minutes from the start of the test. At this point, the first layer of gypsum board protection on the ceiling had completely fallen off and the fuel source was solely the CLT walls.

After the second flashover, room temperatures reached a maximum of 1057°C. Once again the temperature in the room started to fall steadily afterwards.

Figure 4-7: A second flashover takes place, this time the CLT walls are fuelling the fire

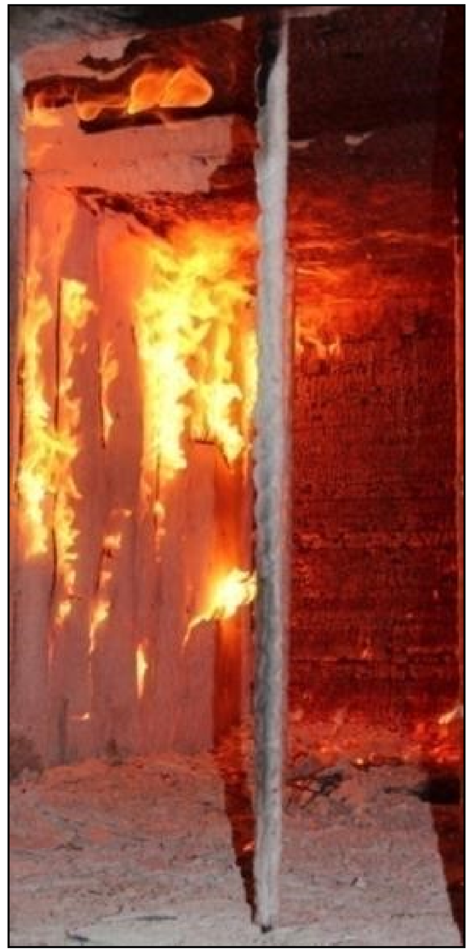

Figure 4-8: Flames escape through the joints of the last layer of gypsum protection

At around 12:49PM, 87 minutes after ignition, the last layer of gypsum board protection on the ceiling fell off. Temperatures in the room continued to decrease and burning kept taking place in the second layer of CLT. The temperature in the room continued to decrease 120 minutes into the test. Just over two hours after ignition (123min) the room fire was extinguished by the firefighters as there was no indication of panel self-extinguishment and the third and last layer of the unprotected CLT panels had started to char.

4.1.2 Heat release rate (HRR)

The room fire in Test 1 exhibited two separate stages of growth, development and decay. Figure 4-9 shows the output HRR and room temperature recorded by the plate thermometer during Test 1. The vertical left axis is for the HRR while the vertical right axis is for the temperature. There was a crash in the HRR recording system that lasted about 22 minutes. During this period of time the HRR data was lost. The system was restarted and was able to start recording the data before the second flashover took place.

The figure shows that following the first flashover the fire reached a maximum HRR value of 4.8 MW. The initial decay was very rapid at the beginning as the room content was consumed and only the two bare CLT walls were burning. After the fire decayed for about 45 minutes, delamination of the first CLT ply exposed fresh wood causing the fire to regain strength. At this point the room underwent a second flashover reaching a maximum HRR of 3.0 MW.

The growth rate of a design fire can be analysed as a parabolic curve known as a t-squared fire so that the HRR is proportional to the time squared. The growth constant "*k",* which is the time in seconds, takes the fire to reach a size of 1.055 MW [**10**] was 115 for the first peak before initial flashover. This growth factor value is associated with upholstered furniture such as the mattress and thin wood furniture such as the night tables in the room. Equation (16) can be used to determine the fire HRR at any time during the growth phase of a t-squared fire. The first growth phase which occurred 3.5 minutes into the test had a growth constant that falls between fast (k = 150) and ultrafast (k = 75) fire growth [**10**].

$$Q = \left({}^{t}/_{k} \right)^{2} \tag{16}$$

The growth factor for the second flashover was about 300 which corresponds to a medium fire growth rate typical in solid wood furniture. The HRR quickly started to decay after reaching the maximum value. This second decay was slower than the first one because the initially protected CLT wall panels were involved in the fire as the gypsum protection had failed by this time in the test.

The temperature recorded by the plate thermometer during the test was plotted alongside the HRR in Figure 4-9. The temperature of the room follows a close relation to the HRR with both curves increasing and decreasing at the same time. There is a small delay in time between the temperature and HRR. This occurs because temperature is a product and depends on HRR. After 120 minutes the HRR and the temperature in the room were still decreasing when the room was manually extinguished. At this point all walls and ceiling panels were charred and self-extinguishment might have occurred. The test had to be stopped as the initially unprotected walls were burning in the last ply and compromising the integrity of the room.

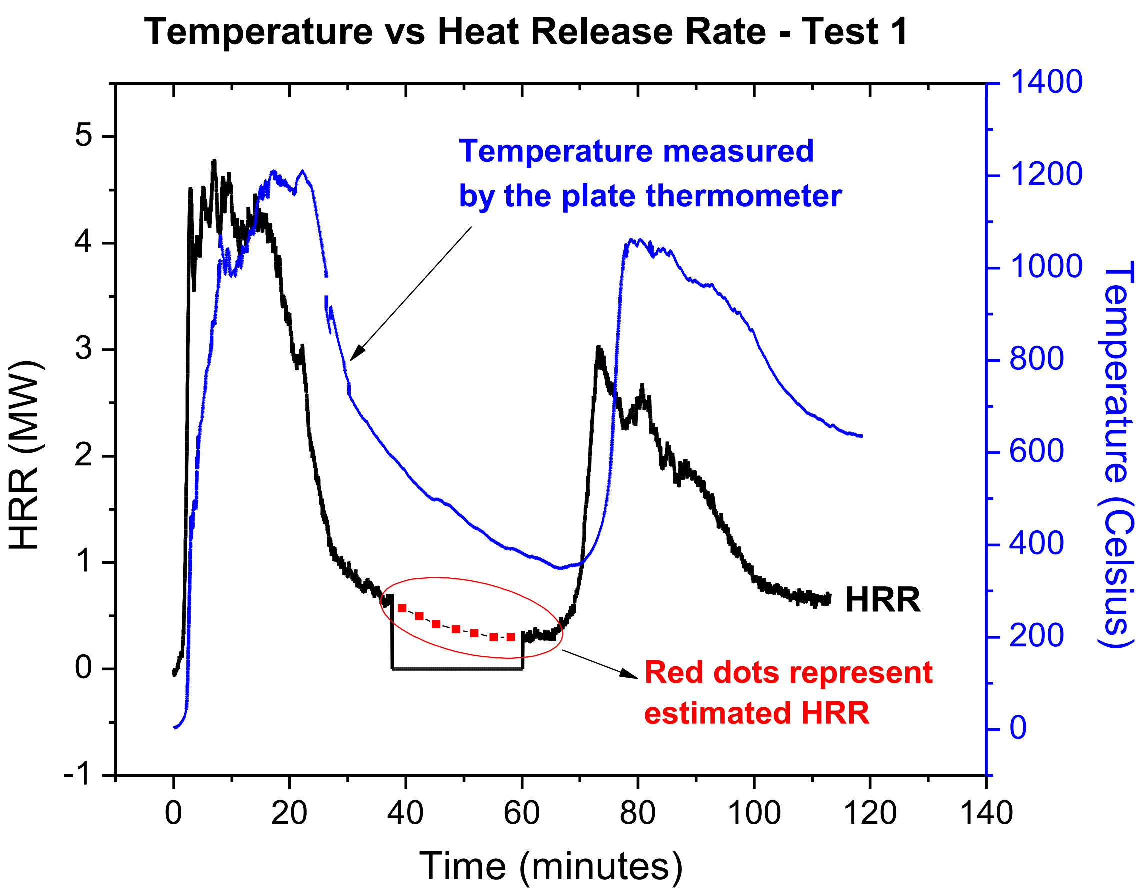

Figure 4-9: HRR and room temperature behaviour during Test 1

4.1.3 Temperature in the room

Figure 4-10 shows the average temperature of the six thermocouples of each tree for Test 1 in order to determine the temperature behaviour at different locations of the room. During the test, one of the thermocouples that were part of thermocouple Tree 4, located at the entrance by the door, became damaged and provided erroneous negative temperature readings. This thermocouple was located at the top of the tree where flames were exiting the room. The average temperature for this tree was calculated using only the remaining five thermocouples.

The average readings from the thermocouple trees and the plate thermometer seem to follow the same trend. Initially there was a rapid increase in temperature indicative of the occurrence of flashover, which occurred five minutes into the test. The dotted line in the figure represents the temperature reading from the plate thermometer. The plate thermometer is capable of recording r temperatures with more accuracy as it accounts for heat radiation of nearby burning surfaces. As shown in the Figure 4-10 the plate thermometer reached a maximum temperature of about 1200 ^{o}C after 24 minutes from the time of ignition. The thermocouple trees measured an average maximum reading of about 1100^{o}C, 14 minutes after ignition. The temperature starts to decrease steadily moments after reaching this maximum. The majority of the contents in the room had been consumed by that time.

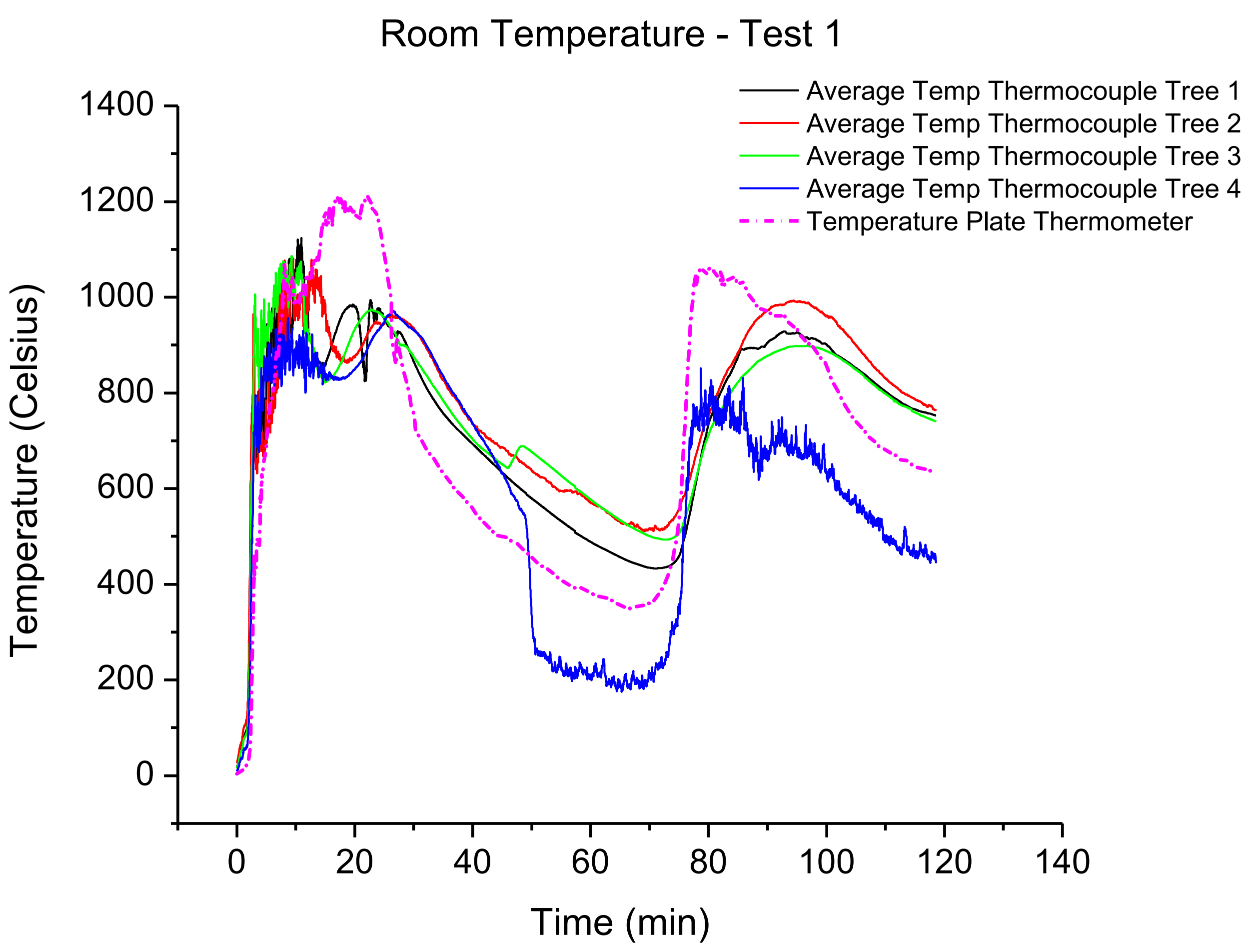

Figure 4-10: Average room temperature during Test 1

The temperature in the room decreased steadily for about 40 minutes. At this point the temperature in the room starts to plateau and then it increased slightly. This slight increase in temperature was the result of flaming in some wall locations due to the delamination of CLT layers.

The temperature measured by all thermocouple trees shown in Figure 4-10was very similar, with the exception of thermocouple Tree 4 which recorded lower temperatures near the floor of the room which is associated with the cool air entering the room. This tree had a failure of the 6^{th} thermocouple located near the ceiling of the room. In all thermocouple trees the temperature of the first five thermocouples record the highest temperature while the sixth thermocouple, nearest to the ceiling, records lower temperatures, as shown in Figure 4-11 - Figure 4-14. Theoretically as the hot gases move to the top of the room the temperature recorded by thermocouple 6 at the top of each tree should record the highest temperature but this is not the case. The height of the room without any gypsum protection on the ceiling and hardwood floor was 2.5 m. The height was close to 2.4 meters once the ceiling gypsum and floor was added. The height of thermocouple 6 in all 4 thermocouple trees was 2.4 measured from the top of the hardwood floor meaning it was located right against the gypsum on the ceiling. The velocity and temperature of the gases varied in accordance to distance from the ceiling [**41**] with a maximum distance depending on the height from the fire and the total Heat Release Rate.

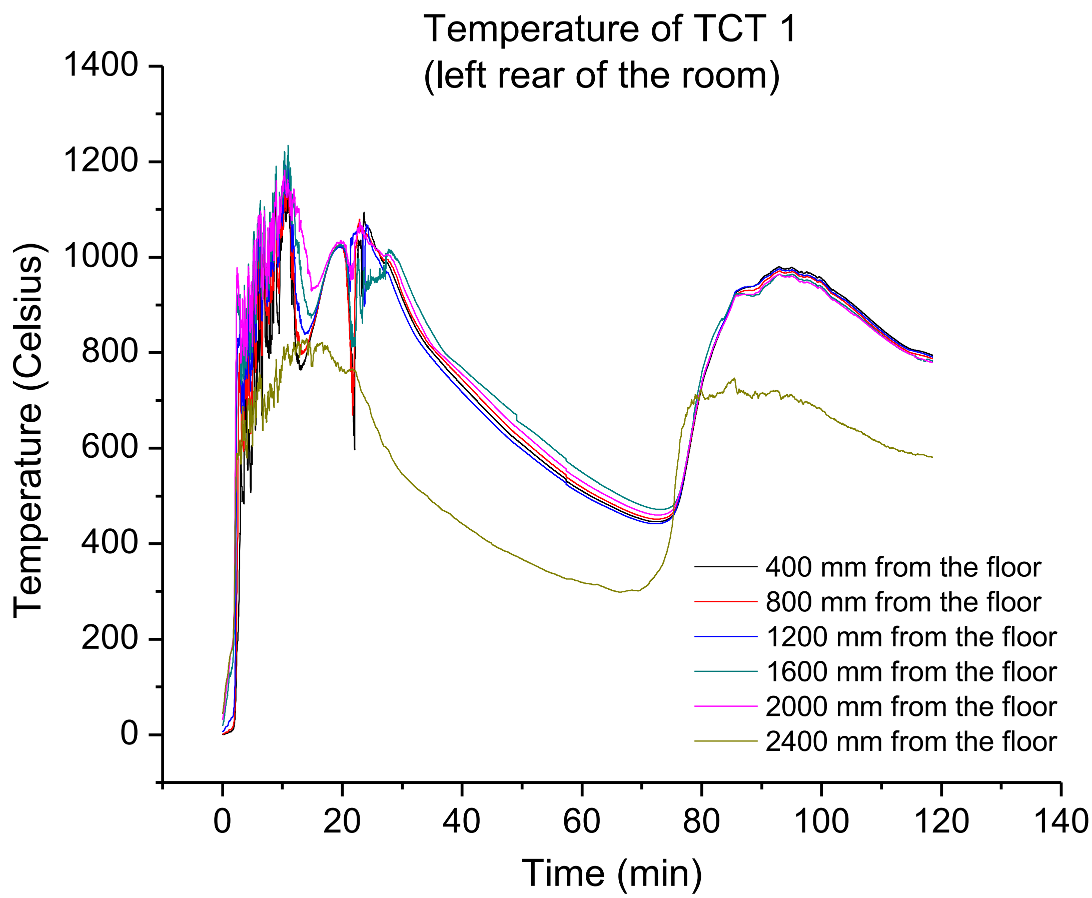

Figure 4-11: Temperature at various heights of the back left of the room

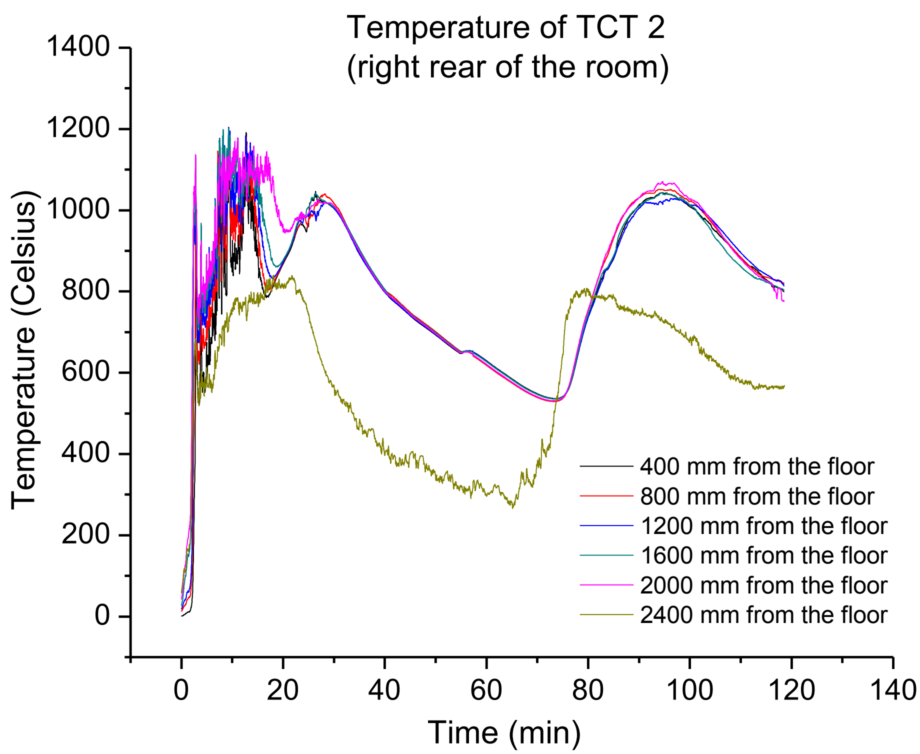

Figure 4-12: Temperature at various heights of the back right of the room

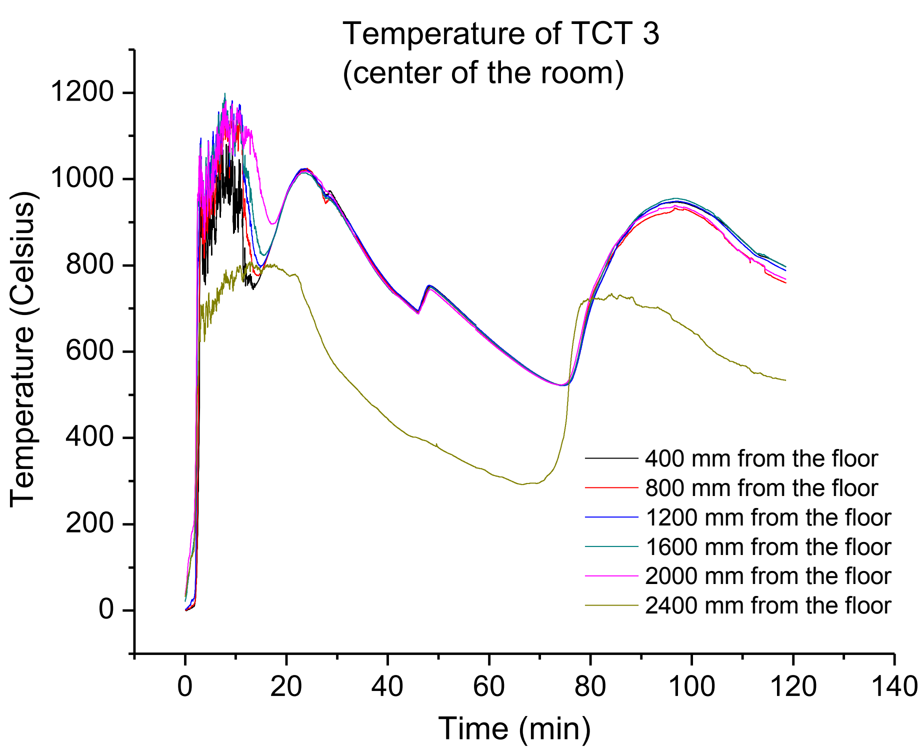

Figure 4-13: Temperature at various heights of the middle of the room

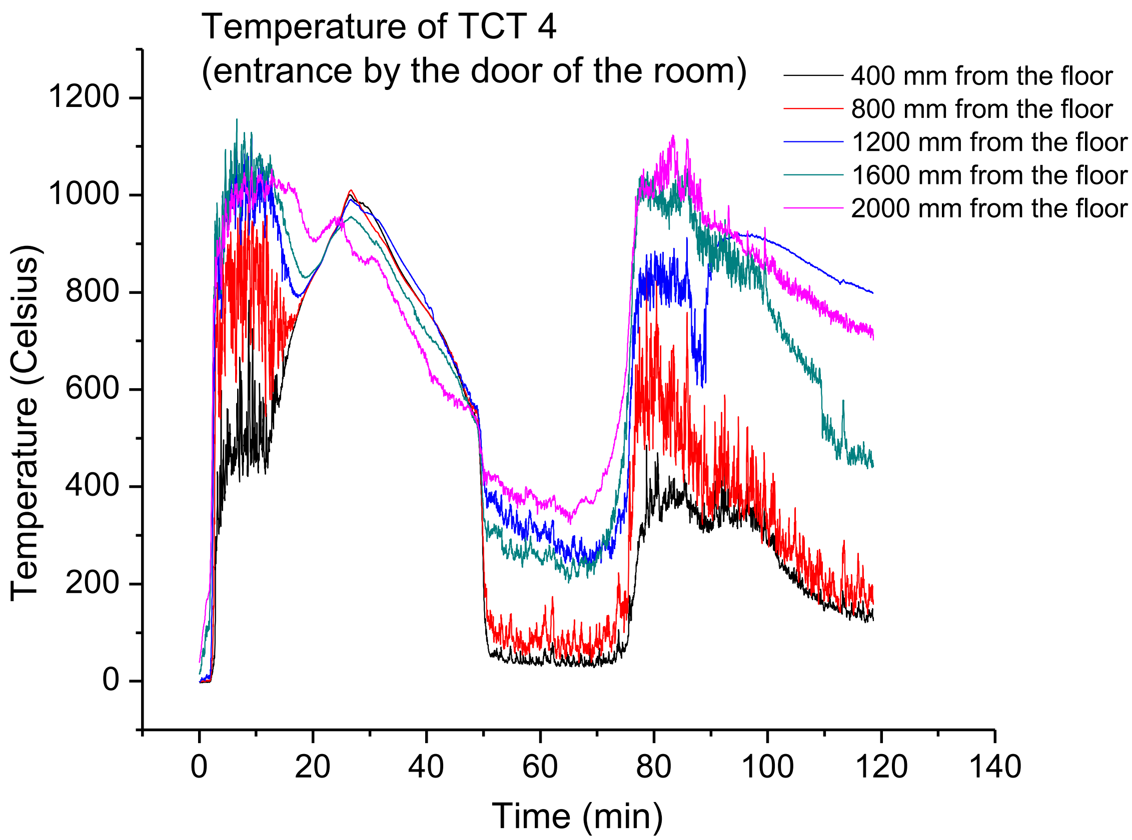

Figure 4-14: Temperature at various heights of the entrance of the room

Thermocouple Tree 4 in Figure 4-14 shows high fluctuations in temperature. This thermocouple tree was located at the entrance of the room where there is a high volume of gases entering and exiting the room. This rapid fluctuation in temperature was not recorded during Test 2 or Test 3. As explained in Chapter 3 Room Fire Test, the construction of the thermocouple trees for Test 1 differed from that of Test 2 and 3. For Test 1, the thermocouples were placed inside a hollow steel tube. Although the thermocouple tree was covered with Fiberfrax ceramic insulation, the 6 thermocouples were not fitted tightly and were able to move slightly. The thermocouples were more tightly fitted in Test 2 and Test 3. Another reason for the high fluctuation could be the ambient temperature during the test. The temperature at the start of the

Test 1 was -1°C as compare to 19°C and 23°C for Test 2 and 3 respectively. Figure 4-14 shows that the higher fluctuation occurs at high temperatures. Consequently at this time the exchange of gases through the room entrance is at its highest as the heat release rate would also be high. The cool gases entering the room might have an effect on the temperature fluctuation recorded by Thermocouple Tree 4 during Test 1.

4.1.4 Temperature at the CLT Cross-section

A number of embedded k-type thermocouples were used to monitor the temperature of the CLT panels throughout the test. Multiple groups of 6 thermocouples each were used at different wall locations. In Test 1, eight total wall groups were used. Six groups were located in the unprotected left wall and two groups on the unprotected back wall. The thermocouples in each group were embedded at 3, 6, 9, 12, 18, and 24 mm from the interior CLT wall surface.

Figure 4-15 to Figure 4-22 show the temperature recorded by the thermocouple wall groups located on the unprotected side wall and rear wall. The point of view for orientation purposes is from inside the room as you enter the room. For example, the right wall refers to the unprotected wall in the right hand side as you enter the room. Each graph has been trimmed at a temperature of 350°C in order to facilitate measuring the time of charring at different depths in each wall group as wood chars at a temperature of about 300°C. In some instances such as in wall Group 2, 6, and 8, it appears as if different depths reached the same temperature at the same time. Each hole was drilled from the outside of the panels which could have led to erroneous thermocouple depths because of human error. In theory, the distance (time) between plotted depths of 3, 6, 9 and 12 mm at each given temperature should be equal.

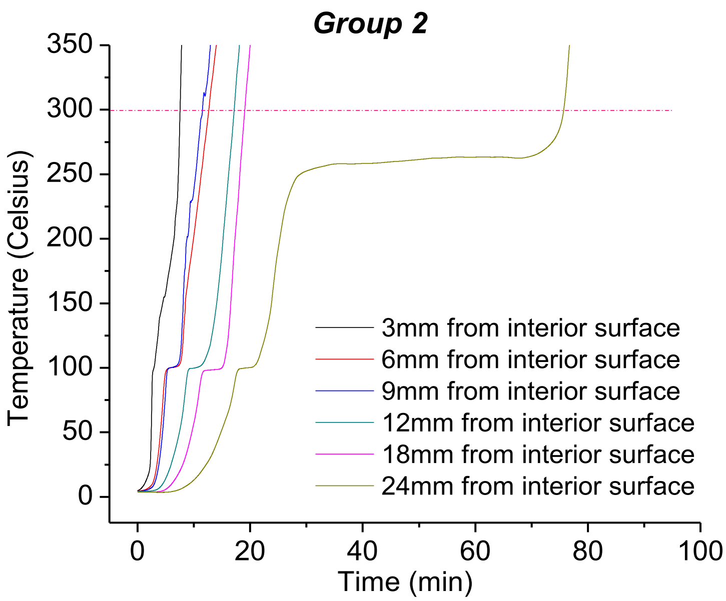

Figure 4-15: Cross-section Temperature Right wall - Top left

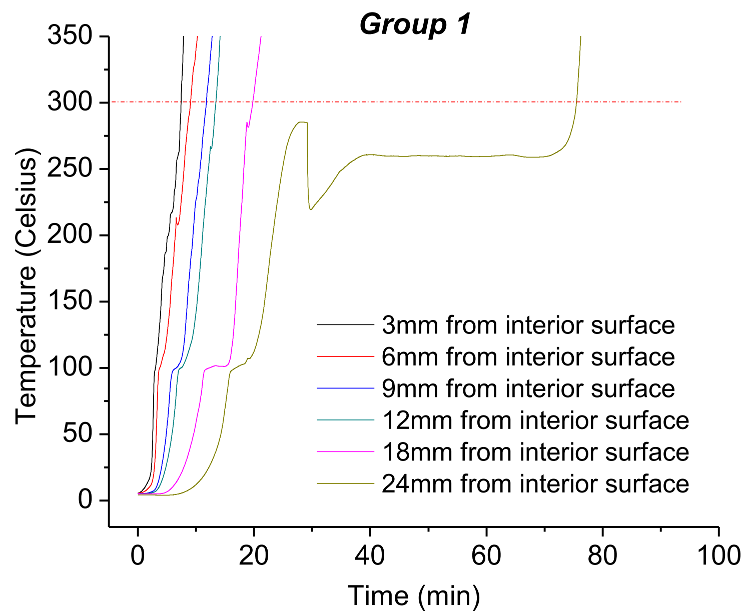

Figure 4-16: Cross-section Temperature Right wall – Top right

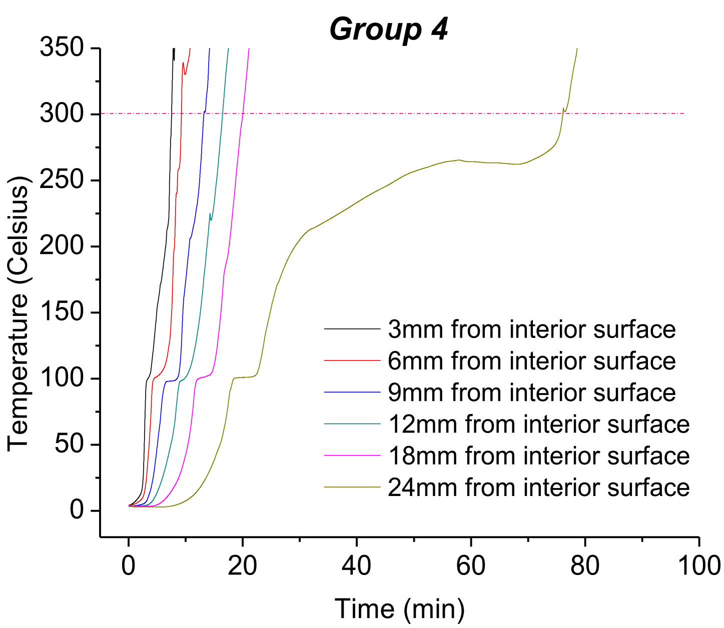

Figure 4-17: Cross-section Temperature Right wall - Middle left

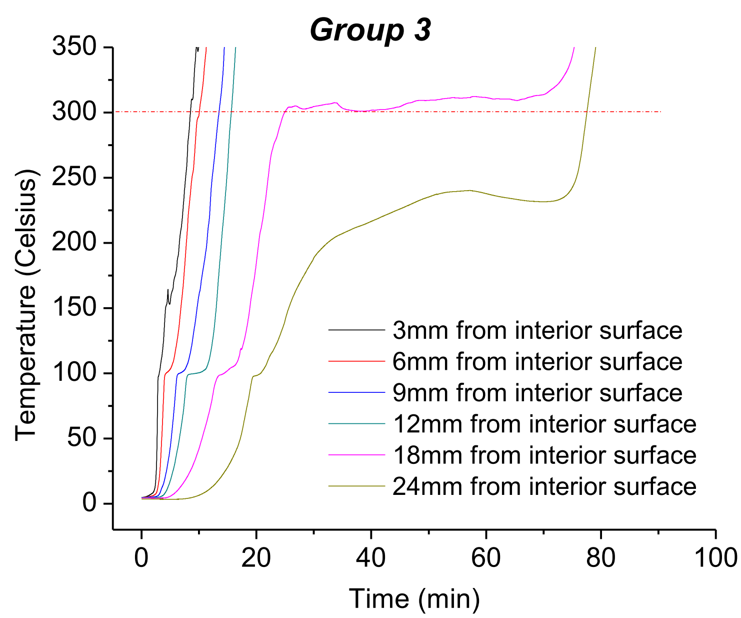

Figure 4-18: Cross-section Temperature Right wall - Middle right

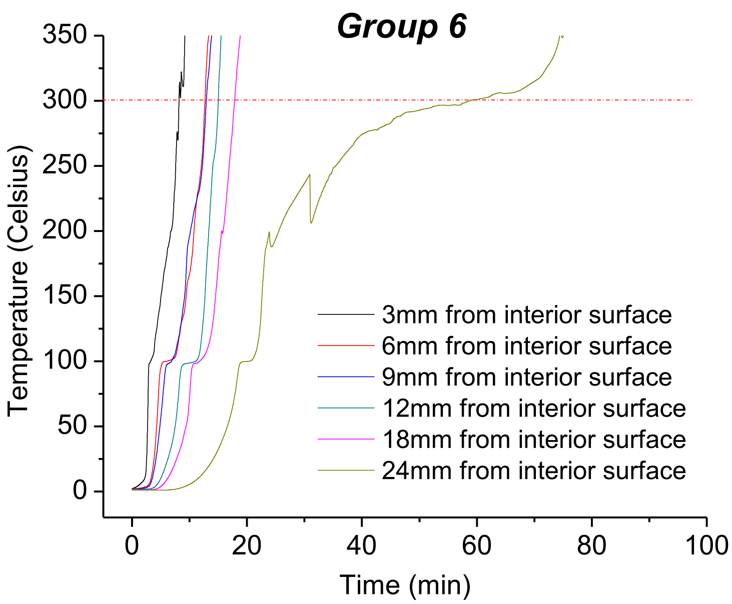

Figure 4-19: Cross-section Temperature
Right wall - Bottom left

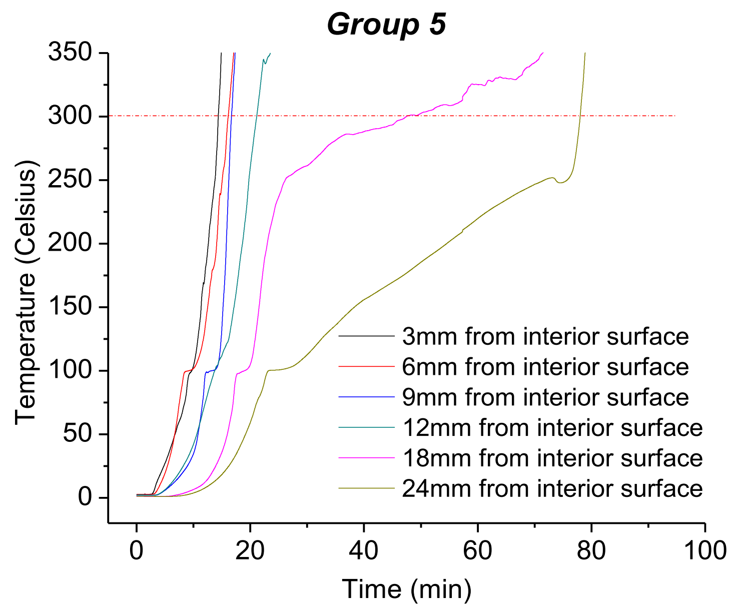

Figure 4-20: Cross-section Temperature
Right wall - Bottom right

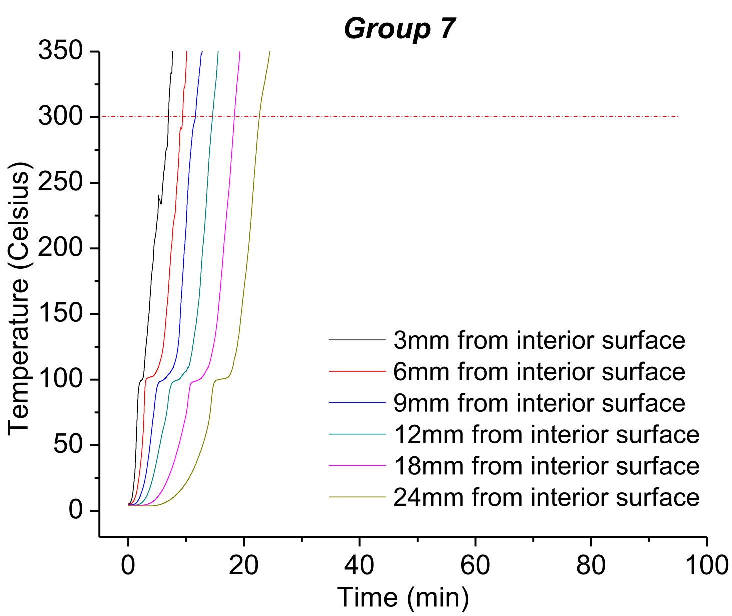

Figure 4-21: Cross-section Temperature
Rear wall – Center top

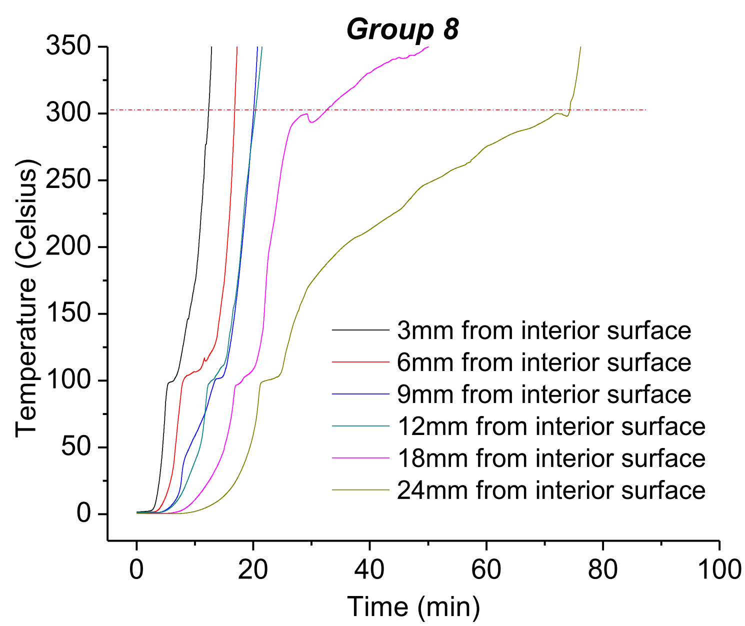

Figure 4-22: Cross-section Temperature
Rear wall – Center bottom

Figure 4-21 and Figure 4-22 show the cross-section temperature of the rear wall panel up to the point of charring at 300°C. Notice how the last embedded thermocouple in Group 8, Figure 4-22, at 24 mm does not char until after 80 minutes. This charring time is substantially slower than Group 7 located right above the first ignited item. The bed's headboard shielded the location of thermocouples in Group 8 during the early stages of the fire which delayed the charring onset during Test 1. Group 7, which was located directly above the bed, recorded the highest temperatures early in the test and that location exhibited a high charring rate.

The temperature recorded by the different thermocouple groups depends on their location in the wall. Group 5, located 0.6 m high of the floor on the right of the side wall was shielded by the long dresser at the beginning of the fire until the time it was consumed by the fire. The temperature rise was slower at this location due to the initial shield provided by the long dresser.

In addition to the embedded thermocouple groups located in the walls, two more groups were embedded on the ceiling to measure the temperature of the CLT-gypsum board interface. These groups contained three thermocouples each. The first thermocouple was located between the two layers of the gypsum boards. The second thermocouple was located at the CLT-gypsum board interface and the third thermocouple was embedded 6 mm into the CLT panel. Figure 4-23 and Figure 4-24 show the temperature recorded by these thermocouples. The added protection of the 2 layers of gypsum board delays the char onset of the panels by over 80 minutes.

The first ignited item in the room was the right side pillow. The most affected area early on in the fire was the back of the room where the bed was directly below the ceiling thermocouple Group 2. Figure 4-24 clearly shows a rapid temperature increase underneath the first layer of gypsum. The temperatures of embedded ceiling thermocouple Group 1, in Figure

4-23, shows a much slower increase. As ceiling thermocouple Group 1 was located away from the burning bed, it experienced lower temperatures resulting in a lower charring rate at that location than the location of ceiling thermocouple Group 2 which was located directly above the bed. The wood underneath the second layer of gypsum started to char just after 80 minutes of fire exposure.

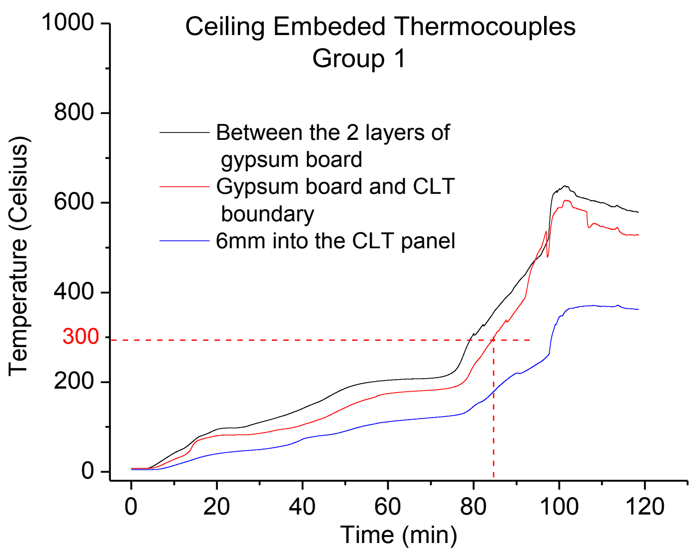

Figure 4-23: Cross-section temperature of protected ceiling, 1.5 m from room entrance

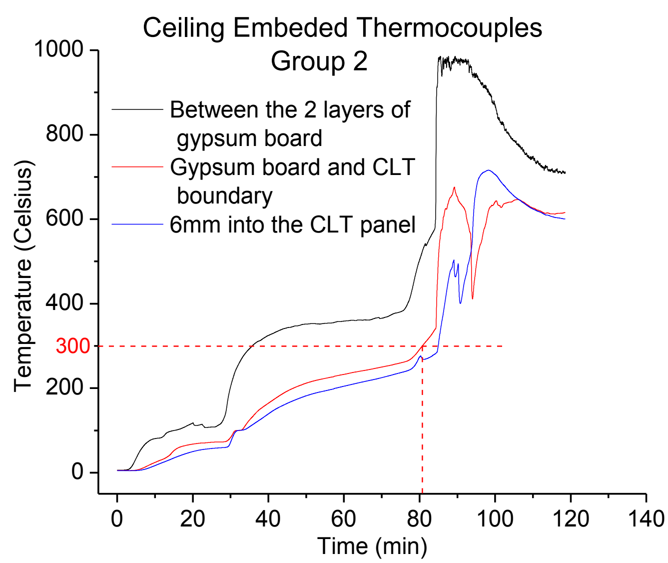

Figure 4-24: Cross-section temperature of protected ceiling, 3.0 m from room entrance back of the room

4.1.5 Charring depth / Remaining panel cross-section

Measurements of the char depth were taken at the end of every test. Once the room was disassembled, the un-affected thickness of each panel was measured at the most severely damaged spot that was visually determined. In some cases, the most severely damaged spot was not easily identified. In those instances, an average of three measurements along the panel was taken. Before each measurement was taken, a steel brush was used to remove all the excess char until the unaffected wood was reached. The result of the clean surface is showed in Figure 4-25. A small hole was drilled trough the panel and then a digital calliper was introduced to record the measurement of the remaining panel thickness. Figure 4-26 shows the remaining thickness of each panel. The initial cross-sectional thickness of the CLT panels was 105mm therefore the total burned depth can be determined by measuring the remaining cross-section.

Figure 4-25: Char is removed to measure remaining panel cross-section

After the room burned for 120 minutes, the protected CLT walls exhibit little charring. Panels 1 and 2 of the front wall only charred in average 13 mm while panel 4, located in the corner adjacent to the unprotected back wall, charred 25 mm. The first signs of delamination which led to the second flashover occurred at the corner between panel 4 and panel 8. Panel 3, also on the left side wall but closer to the entrance only charred about 10 mm. In summary, the unprotected CLT walls experienced the highest charring depths ranging between 71-80 mm. The ceiling panels had a charring depth between 33-41 mm and the protected walls 10-25 mm.

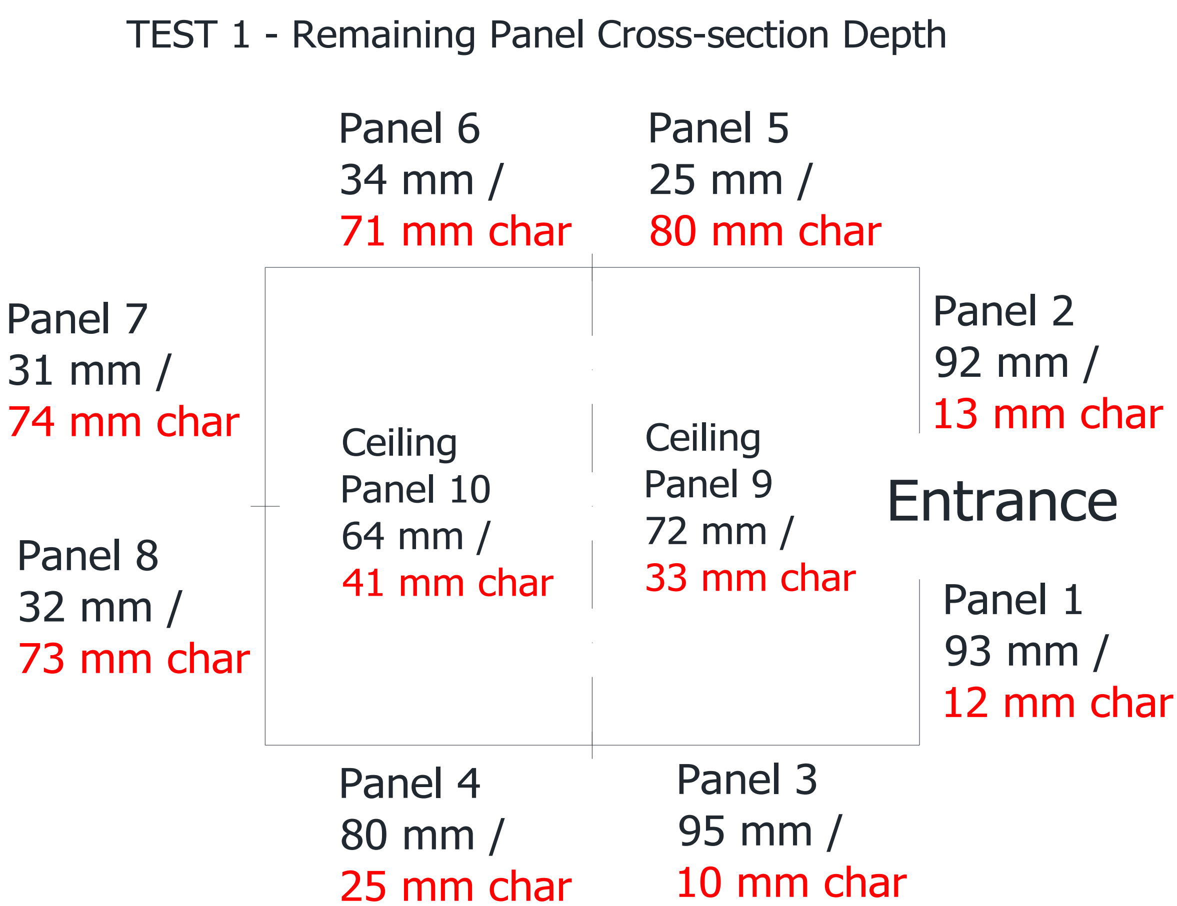

Figure 4-26: Plan view sketch of remaining cross-section thickness of CLT wall and ceiling panels after Test 1

The charring depth throughout the test of the right side wall and rear wall are presented in Figure 4-27. The time at which the embedded thermocouples in each group reach 300°C is recorded. These times together with the embedded depth of each thermocouple is graphed to show the movement of the char front at each location. The char front at the top of the rear wall (Group 7) moved fastest as it was located directly above the bed, where the fire was started. The bottom of the right wall (Group 5) close to the room entrance moved the slowest. This was the thermocouple group that was initially covered by the long dresser.

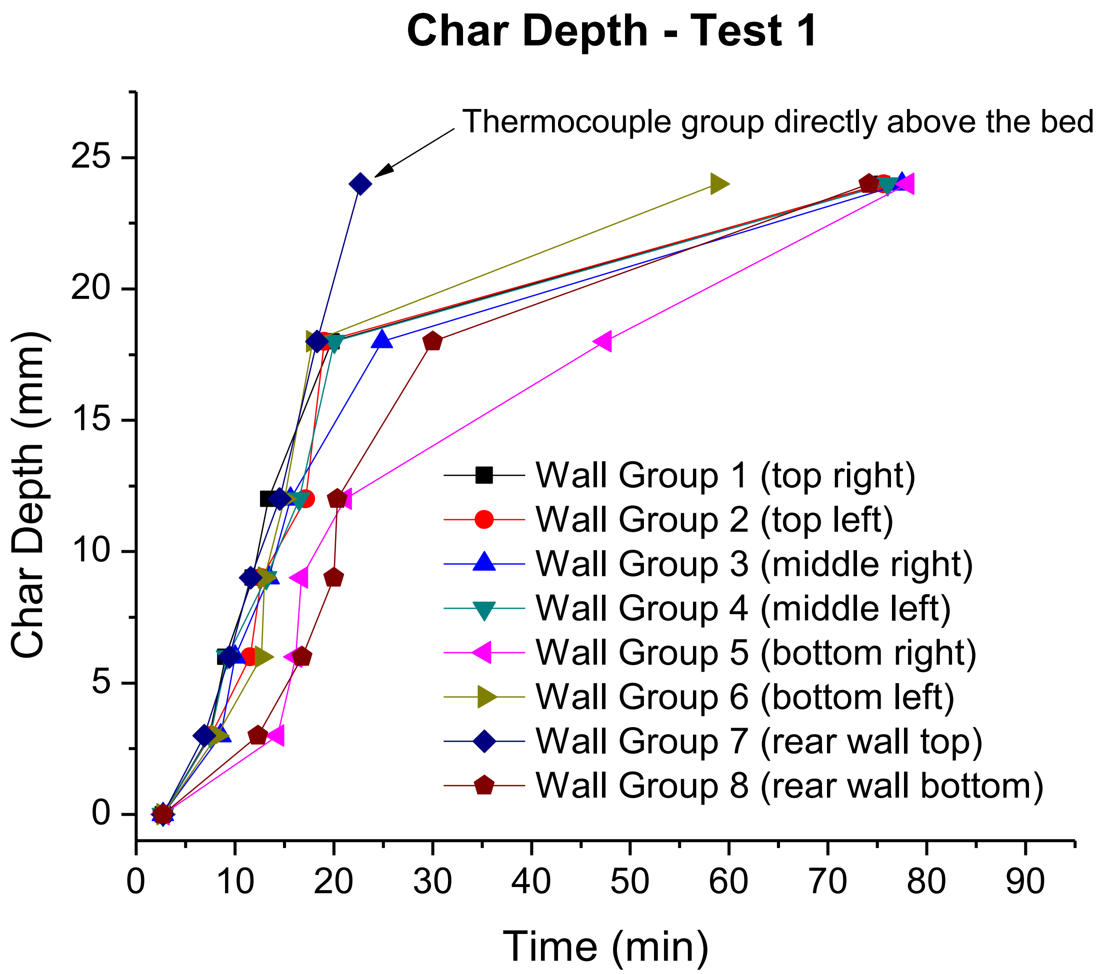

Figure 4-27: Charring depth of thermocouple groups on the right side wall and rear wall

4.1.6 Charring rate

The charring rates at different locations of the CLT wall panel were calculated at multiple locations. Having an understanding of the way CLT panels char during a real non-standard fire can aid in better predicting the performance of CLT panels in fire. The charring rate was calculated by determining the time at which each pre-defined embedded thermocouple reached the theoretical charring temperature of 300°C as well as their respective embedment distance. The charring rate at a certain point was determined by dividing the depth of embedment of that particular point by the difference in time between charring of that particular point and the CLT surface. The time at which the room temperature reached 300°C was considered as the time of charring of the surface. For example, the charring rate, given in mm/min for thermocouple number 3 embedded 9 mm into the wood was calculated as shown in Equation (17).

$$CR_{avg,9} = \frac{9\ mm}{(t_{300,9} - t_{300,0})min} \tag{17}$$

Where:

$t_{300,0} = time\ at\ which\ the\ temperature\ of\ the\ surface\ reaches\ 300°C$

$t_{300,9} = time\ at\ which\ the\ temperature\ at\ 9\ mm\ into\ the\ wood\ reaches\ 300°C$

The charring rate of the panel was calculated at six different locations on the unprotected side wall and at two locations on the unprotected rear wall. Figure 4-28 shows the graphs for the average and instantaneous charring rates of the first four thermocouple wall groups on the side walls. The average charring rate is calculated by dividing the depth at the point of interests by the time it took to reach 300°C. The average charring method provides less variable results. The instantaneous charring rate is calculated by taking the difference in distance between two depths and dividing it by the difference in time for each point to reach 300°C. In theory, the instantaneous charring rate should provide more accurate results but could lead to very variable data if the predefined embedment thermocouple depths are not accurate.

Table 4-1 shows a statistical analysis including the mean charring rate as well as the fastest and slowest charring rate of each wall group. Each thermocouple wall group started with a char rate close to 0.6 mm/min except for Group 5 which was located directly behind the long dresser and therefore protected during the early stages of the fire. The charring rate quickly rose in each instant until it reached its maximum of about 1.1 mm/min around 15 minutes from the ignition of the fire. As the char layer developed in depth, it better insulates the unburned wood underneath. This is the reasoning for the incremental decrease in charring rate as the test progresses.

Figure 4-28 and Figure 4-29 show the average and instantaneous charring rate of wall Groups 1 through 8 located on the unprotected right and rear walls. Thermocouple Group 5 and 6 are located at the bottom of the unprotected right wall. Thermocouple Group 7 is embedded directly above the bed which caused it to have a relatively high charring rate. Group 8 was embedded behind the bed's headboard which protected that section of the CLT for the first stages of the fire. The variable behaviour of the instantaneous charring rate in wall Group 5 and 6 is due to errors in the embedment depth of the thermocouples. Wall Group 6 shown in Figure 4-19 thermocouples 2 and 3, at 6 mm and 9 mm respectively appear to record the same temperature. Similarly, wall Group 5 shown in Figure 4-20 thermocouples 1 and 2 and thermocouples 3 and 4 appear to record the same temperature. These results indicated that the actual depth of the thermocouples was not at the required depth resulting in erroneous results of the instantaneous charring rate calculations.

Table 4-2 summarizes the average and instantaneous charring rates of these groups. The direct contact with the early bed flames increases Group 7's charring rate average to 0.96 mm/min while the initial protection of the headboard slowed the rate of charring of Group 8 to 0.46 mm/min.

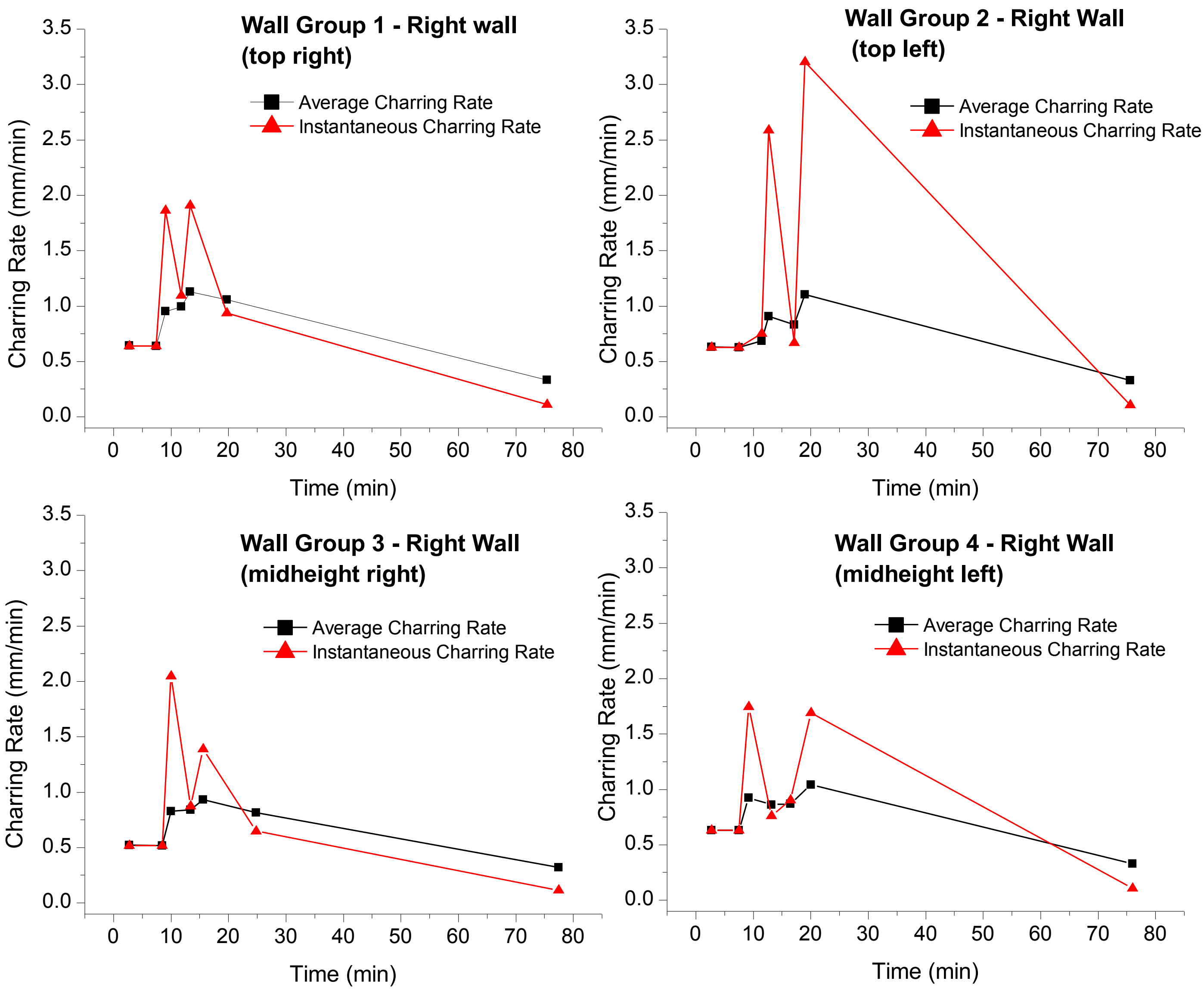

Figure 4-28: Average and Instantaneous charring rate on the unprotected right side wall

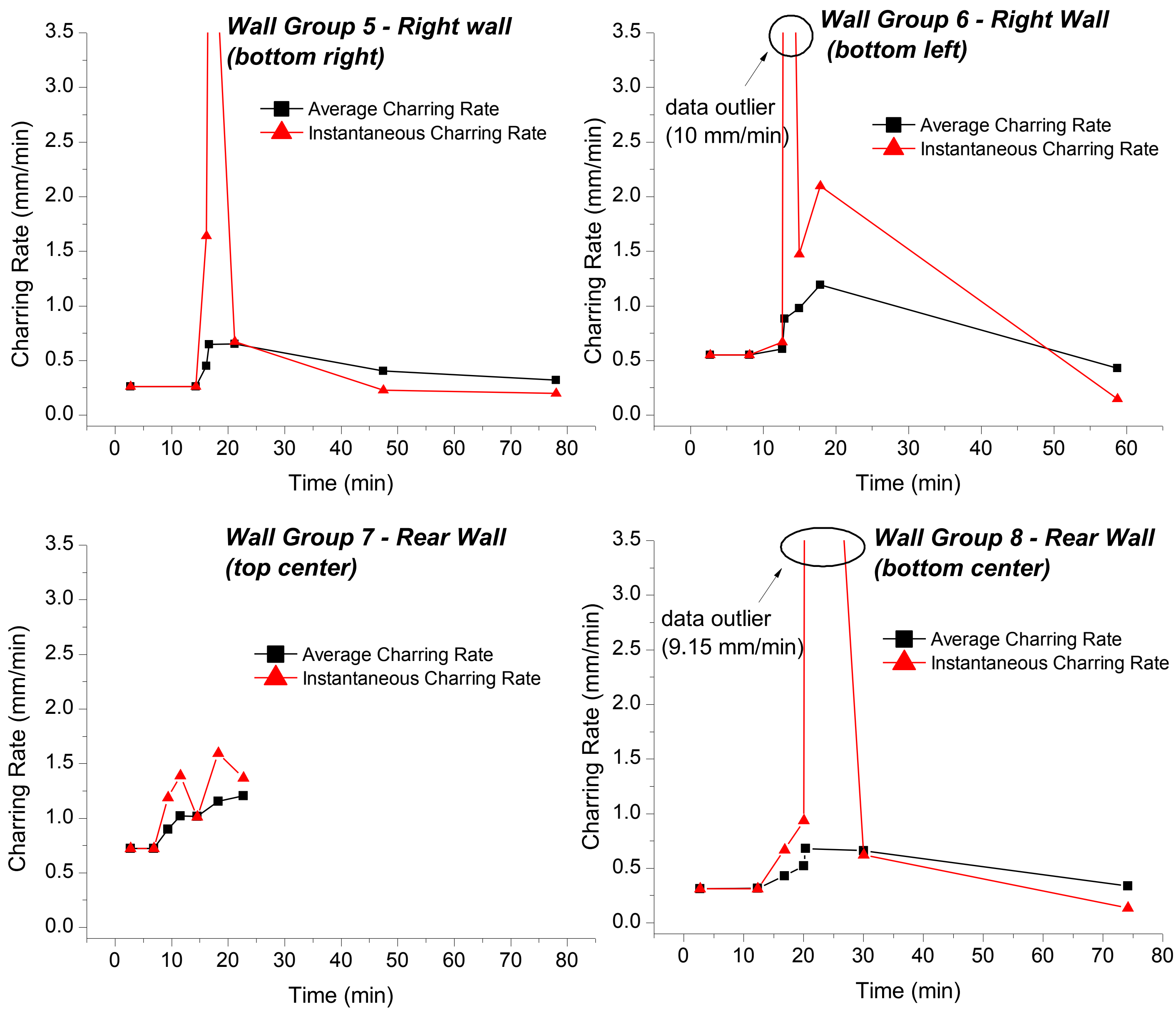

Figure 4-29: Average and Instantaneous charring rate on the unprotected right side wall and rear wall

Table 4-1: Statistical analysis of the average charring rate of side wall and rear wall

Charring Rate Average	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Group 1	7	0.81914	0.28965	0.33	0.95	1.128
Group 2	7	0.729	0.24629	0.329	0.682	1.103
Group 3	7	0.68114	0.22688	0.321	0.813	0.932
Group 4	7	0.75386	0.24073	0.327	0.861	1.038
Group 5	7	0.426	0.16636	0.259	0.402	0.651
Group 6	7	0.73971	0.27831	0.428	0.604	1.189
Group 7	7	0.96157	0.19199	0.72	1.016	1.202
Group 8	7	0.46371	0.15968	0.31	0.426	0.681

Table 4-2: Statistical analysis of the instantaneous charring rate of side wall and rear wall

Charring Rate Instantaneous	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Group 1	7	1.02566	0.66223	0.10774	0.93648	1.90597
Group 2	7	1.22326	1.17387	0.10599	0.66785	3.20171
Group 3	7	0.87189	0.64886	0.11404	0.64774	2.04778
Group 4	7	0.92216	0.59578	0.10718	0.75853	1.74419
Group 5	7	1.24391	1.92717	0.19602	0.25884	5.45455
Group 6	7	2.2121	3.49724	0.14659	0.66667	10
Group 7	7	1.14131	0.33805	0.72155	1.18751	1.59109
Group 8	7	1.73293	3.28005	0.13589	0.62105	9.14634

The calculated average charring rate on the wall groups range from 0.32 mm/min at the end of the test to as high as 1.13 mm/min while the room heat release rate was at its peak. The mean of the calculated average charring rate on the eight thermocouple wall groups was about 0.69 mm/min. This charring rate is slightly higher than the theoretical value of 0.65 mm/min used in fire resistance rating calculations. The instantaneous charring rates on the eight thermocouple wall groups had a mean value of about 1.29 mm/min. This charring rate is substantially higher that the theoretical value of 0.65 mm/min. This could be due to erroneous depths for some of the embedded wall thermocouples making two thermocouples at different depths appear to reach 300°C in similar times.

4.1.7 Premature delamination

The main reason for the re-ignition of the room after it was almost out was delamination of CLT plies before being fully charred. The newly exposed wood served as added fuel causing the HRR and temperature to increase. The polyurethane adhesive used for holding the plies together melts at approximately 200°C which causes the unburnt part of the plies to delaminate before they char. Pictures of the test room taken after the fire was extinguished revealed the delamination of the right wall and ceiling. Figure 4-30 shows the adhesive failure as the second CLT ply is delaminated on the right side wall. Similarly on the ceiling, which was originally protected by two layers of gypsum board, Figure 4-31 shows the failure of the first CLT ceiling ply.

Figure 4-30: Delamination of 2nd ply on the unprotected right wall

Figure 4-31: Delamination of the 1st ply on the originally protected ceiling

Rearranging Equation (1) used for determining the temperature of wood below the char layers we can calculate the thickness of the unburned cross-section of the plies. The resulting remaining thickness is 6.4 mm using the given values and Equation (18). The calculated remaining ply thickness was similar to the measurements taken after the test.

$$T = T_i + (T_p - T_i)\left(1 - \frac{x}{a}\right)^2$$

$$x = \left[1 - \sqrt{\frac{T - T_i}{T_p - T_i}}\right] \times a \tag{18}$$

Where:

$x = distance\ below\ the\ char\ layer$

$T = adhesive\ melting\ temperature = 200°C$

$T_p = temperature\ at\ which\ charring\ starts = 300°C$

$T_i = initial\ temperature\ of\ the\ wood = -1°C$

$a = thickness\ of\ the\ heat\ affected\ layer = 35\ mm$

4.2 Test 2 - Unprotected Right Wall and Left Wall

The second room fire test was conducted on the morning of May 9, 2013. After the observations made during the first test and the evaluation of the data obtained, it was concluded that the second flashover was due to the radiation exchange between the two adjacent unprotected walls. Flaming underneath the first layer of CLT due to delamination started at the rear right corner of the room where both unprotected walls met. It was decided to remove this interaction in order to reduce the likelihood of delamination.

The interior dimensions of the CLT room were 4.5 m deep by 3.5 m wide and 2.5 m in height. The room had only one opening (door). For this test the left wall and the right side wall as you enter the room were left unprotected while the rest of the walls and the ceiling were protected with 2 layers of ½ inch Type X gypsum board. Figure 4-32 displays the room dimensions as well as the protected and unprotected surfaces. The room contents were similar to those of Test 1.

Figure 4-33 shows the fully furnished and instrumented room before the second room fire test.

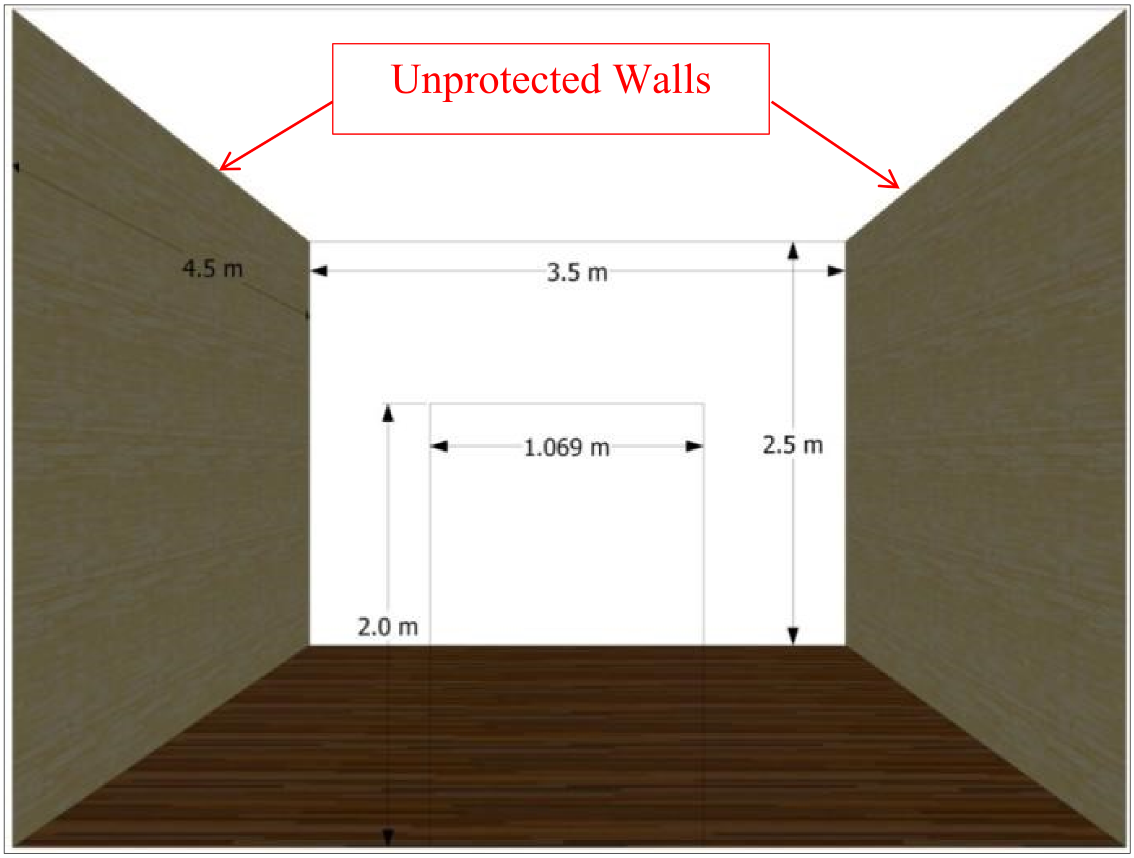

Figure 4-32: Test 2 interior room dimensions.

Figure 4-33: Furniture used as fuel for Test 2 including bed, night tables, and dressers

The second room test eliminated having two unprotected adjacent walls, however the total area of unprotected surfaces increased from 20 m^2 in the first test to 22.5 m^2 (59.4 % of total wall surface area in the room). This is because the side walls were 1 meter longer than the back and front walls. Although the walls were no longer adjacent to each other, the total unprotected surface area increased thus increasing the fuel load initially available to burn.

Four thermocouple trees were used to measure the temperature in the room. Each thermocouple tree had 6 thermocouples at 0.4 m, 0.8 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m from the floor. The thermocouple trees were not shielded by a steel pipe as in the first test. Instead, the individual thermocouples were wrapped around a thicker heavily insulated thermocouple cable and positioned at their required elevations. A layer of ½ inch Fibrefrax insulation was then used to wrap all the thermocouple trees.

For this test there were 4 wall thermocouple groups in each of the 2 unprotected walls. As in the first test, the thermocouples were embedded at 3, 6, 9, 12, 18, and 24 mm from the interior wall surface. The 4 thermocouple groups were located geometrically equidistant from each other on both the 4.5 m by 2.5 m walls. Once again all three exhaust fans in the facility were operating at 75% of their maximum capacity throughout the test.

It is important to point out that during the construction of the second room, the fire caulking protection sealant was accidentally omitted at the panel to panel wall and ceiling lap joints. The ceiling to walls panel joints were properly sealed as well as the wall to wall panels forming the room corners. As a result, the CLT panels that make up the left wall, right wall, and back walls were not properly sealed.

4.2.1 Description of the test

The room was manually ignited by the lab technician using a propane burner at 11:12AM. The temperature of the room at the time of ignition was 19°C. The first ignited item was the right pillow on top of the bed. Once the pillow reached self-sustained burning the pilot propane flame was removed. A heavy layer of black smoke started to develop in the ceiling as the entire bed top was engulfed in flames. The fire quickly spread to the night tables adjacent to the bed. Flashover took place, just 4 minutes after ignition. From the video camera recordings, the furniture appeared to have been consumed 16 minutes after ignition. Figure 4-34 shows the room temperature during the second test measured by four thermocouple trees and a plate thermometer

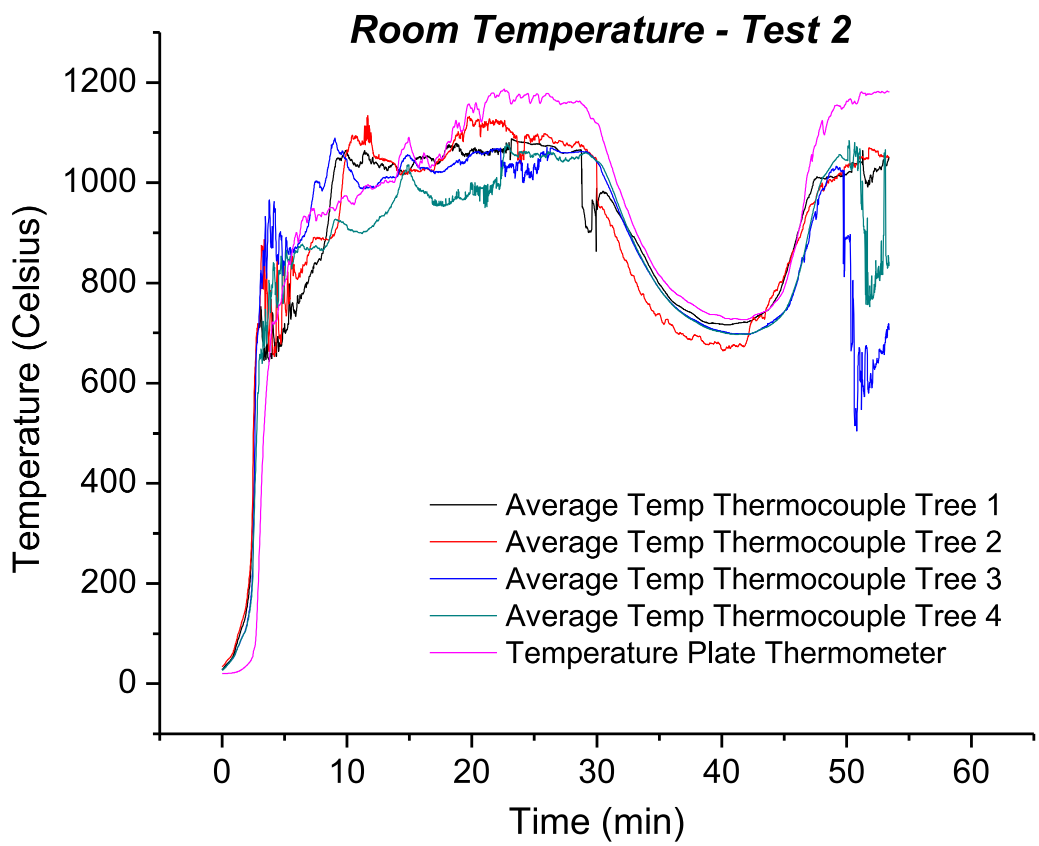

Figure 4-34: Room temperature in Test 2 measured by thermocouple trees and plate thermometer

The maximum energy output recorded was 6.3 MW at 11:20AM or 7 minutes from the start of the test. Flames started exiting the room after flashover, impinging on the unprotected exterior facade around the room entrance. This required firefighters to intervene and spray the exterior of the panels at the entrance to avoid ignition. The test lasted about 57 minutes after which the firefighters intervened and put out the fire.

Similar to the first test, the first layer of CLT delaminated creating a re-ignition of the fire in the room. The first CLT ply was not completely charred before ply delamination started causing fresh wood to be exposed to the fire. The unsealed joint at the side walls was the area where delamination started. The flames quickly extended to the ceiling and caused a second flashover at 11:59 AM. The maximum HRR was about 6.3 MW, as it can be seen in Figure 4-36.

11:51 AM

11:53 AM

11:54 AM

11:58 AM

Figure 4-35: Test 2 CLT ply delamination and progression of room re-ignition.

4.2.2 Heat release rate

Figure 4-36 illustrates the Heat Release Rate during the test. As shown in the figure, flashover occurred at approximately 4 minutes. The heat release rate reached a maximum of 6.3 MW and then started to decrease slowly. About 30 minutes after the heat release system started recording, there was a malfunction of the recording of the mass flow of the exiting combustion gases hence the heat release rate could not be computed. The HRR was not measured pass the 30 minutes mark but it can be assumed that the maximum HRR occurred moments after the first flashover due to the greater availability of fuel loads in the room. During the second flashover only the side walls were involved and therefore it is unlikely that a higher HRR would have been achieved.

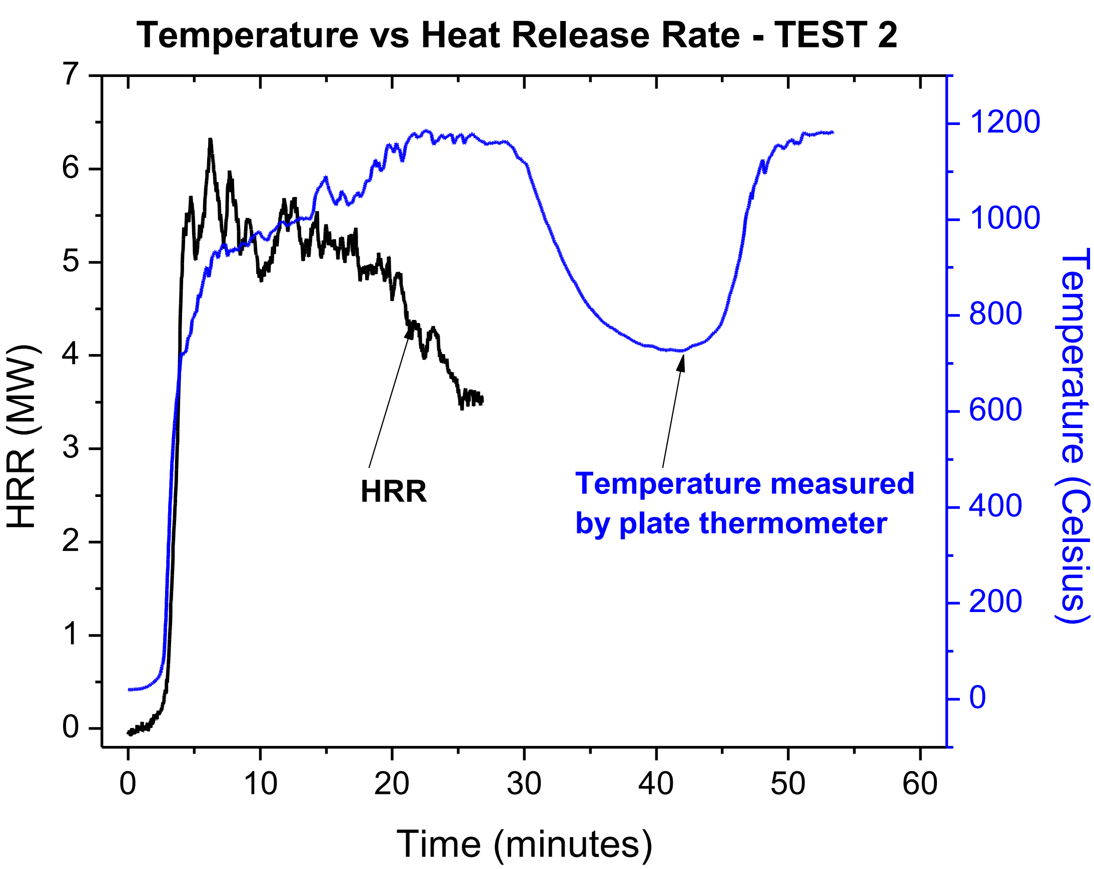

Figure 4-36: Heat Release Rate and Temperature during Test 2

Once the fire reached steady state, about 16 minutes into the test, some gases were observed escaping through the unsealed lap joint along the unprotected side walls Figure 4-37 (left). This gas exchange allowed for charring at the lap joint increasing the gap and allowing even more gases to escape. Flames started to exit through the now widened gaps 49 minutes after the start of the test Figure 4-37 (right). An attempt to fill the gaps with Fibrefrax insulation during the test proved futile as the gaps extended along the entire wall.

Figure 4-37: Failure of lap joint along the unprotected left wall

The ceiling of the room was initially protected with 2 layers of gypsum board but also suffered failure of the lap joint due to lack of application of fire caulking sealant. Although it took longer than the unprotected side walls, smoke started escaping through the lap joint just 39 minutes into the test as shown in Figure 4-38. The flames exiting the lap joints were extinguished using water so the test was not affected by this. It demonstrated clearly however the importance of sealing lap joints of CLT panels to prevent early fire spread from the compartment of fire to adjacent compartments. Table 4-3 shows the time of each of the relevant events during Test 2.

Figure 4-38: Failure of lap joint along the protected ceiling

Table 4-3: Record of events - Test 2

Time	Time from ignition (min)	Events
11:13 AM	0	First ignited item (right pillow in the bed) reaches sustained burning
11:14 AM	1	Black thick smoke starts to develop.
11:16 AM	3	Entire bed covers are engulfed in fire.
11:18 AM	5	Flash over.
11:19 AM	6	Flames are exiting the door and have started to impinge on the outside room panel surfaces.

11:21 AM	8	Fire fighters intervene to put out the outside of the room that have started to catch on fire.
11:29 AM	16	Smoke and soot is starting to exit through the unsealed lap joints along the side walls.
11:45 AM	32	All furniture has been consumed at this point.
11:50 AM	37	Flames start to seep along the joints of the last layer of gypsum protection on the ceiling.
11:51 AM	38	Thermocouple Tree 2 has collapsed due to gypsum falloff from the ceiling.
11:53 AM	40	The right unprotected wall starts to burn more vigorously due to the onset delamination of the first CLT ply.
11:57 AM	44	Entire left wall is now involved in vigorous combustion
11:59 AM	46	Second flashover takes place
12:00 PM	47	Flames exiting the room along the left wall lap joint
12:02 PM	49	Flames exiting the room along the right wall lap joint
12:09 PM	56	Fire fighters intervene and the room fire is put out

The gypsum board protection on the back wall, front wall and ceiling performed as expected. During the first decay phase, after the contents in the room had been consumed, all of the initially protected surfaces were still covered by at least one layer of gypsum boards. Table 4-4 shows the failure times of the two layers of gypsum board on the front wall, back wall and ceiling. Falloff data for gypsum board placed in the interior of the front wall was not gathered as there was no way to visually monitor when the boards failed. In summary, the first layer of gypsum board to fail was at the ceiling after 27 minutes. The first layer of gypsum board on the back wall fell off after 31 minutes of fire exposure. The second layer of gypsum board remained largely in place in the back wall and front wall but failed after 45 minutes in the ceiling.

Table 4-4: Gypsum board fallout time of protected surfaces

	First layer (Closest to the Fire)	Second layer (next to the CLT panel)
Front Wall	No data available	Some cracks were present. More than 85% remained in place when fire was put out
Back Wall	11:44 AM – (31 minutes)	Some cracks were present. More than 80% remained in place when fire was put out
Ceiling	11:40 AM – (27 minutes)	11:58 AM – (45 minutes)

4.2.3 Temperature in the room

The temperature in the room was recorded using 4 thermocouple trees as well as 1 plate thermometer. Thermocouple Trees 1 and 2 were located at the back of the room at each side of the bed. Thermocouple Tree 3 was located near the center of the room by the foot of the bed. Thermocouple Tree 4 was positioned at the entrance of the room. Figure 4-39 to Figure 4-42 show the temperature of the room at different locations and elevations measured by four thermocouple trees. Given their position in the room and their proximity to the burning objects, each thermocouple tree records slightly different temperatures during the first few minutes of the test.

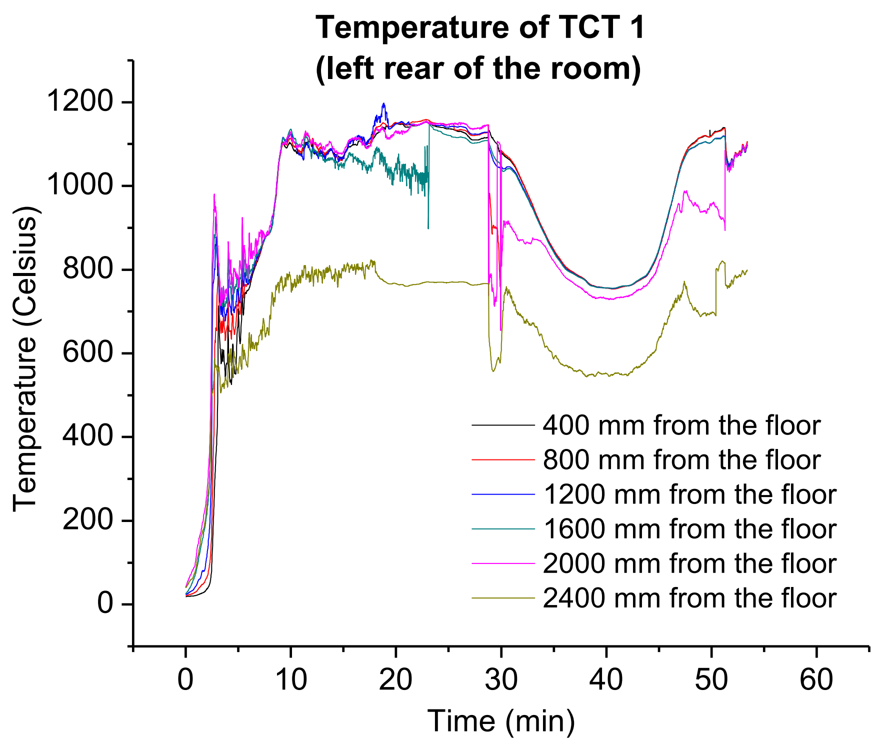

Figure 4-39: Room temperature recorded by thermocouple Tree 1

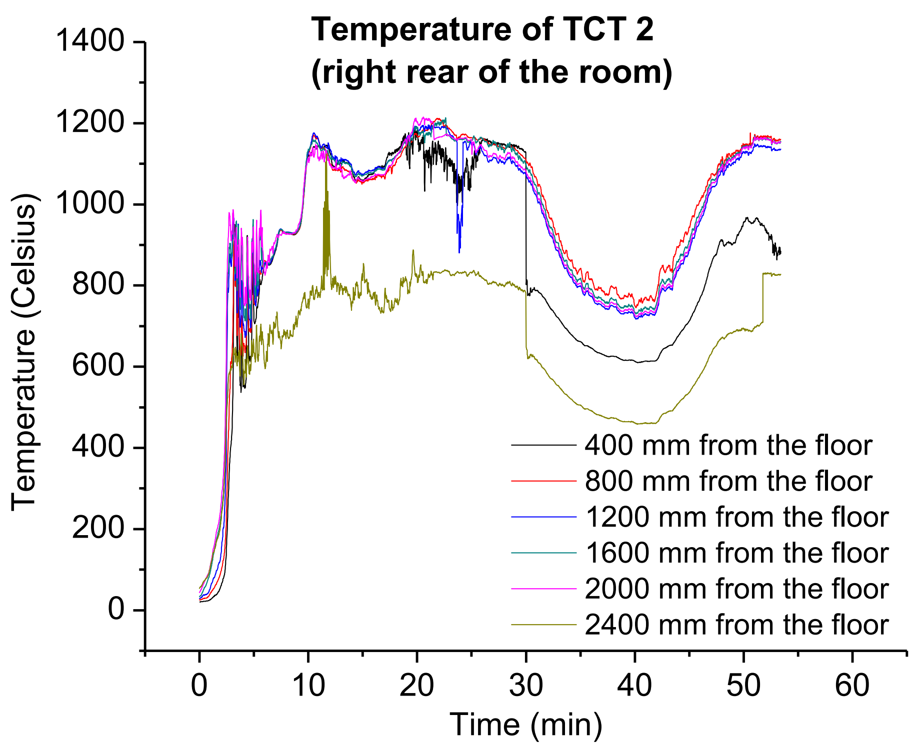

Figure 4-40: Room temperature recorded by thermocouple Tree 2

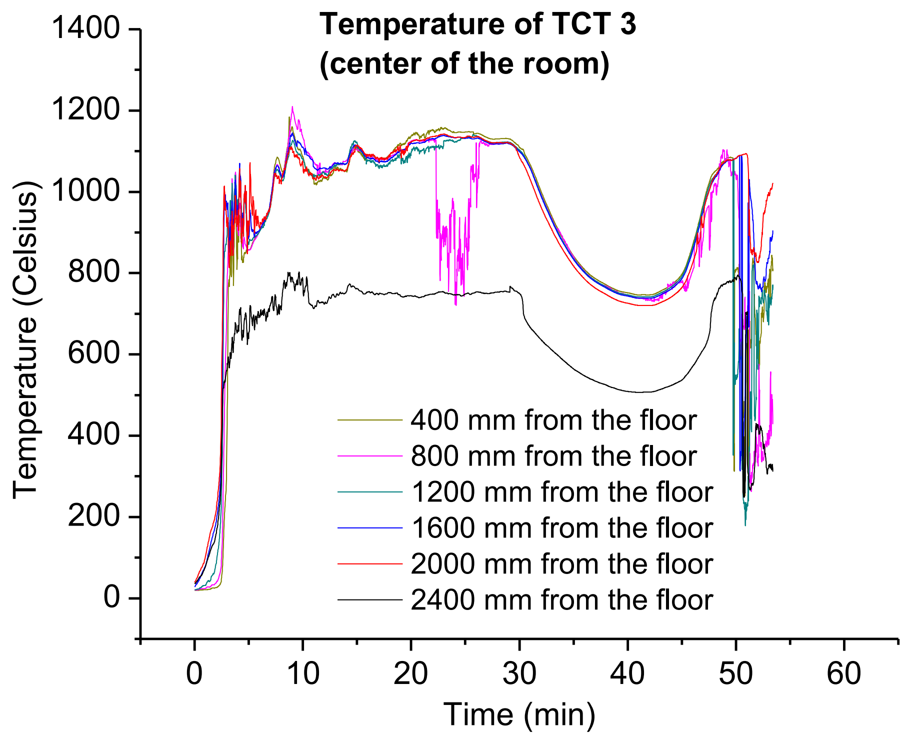

Figure 4-41: Room temperature recorded by thermocouple Tree 3

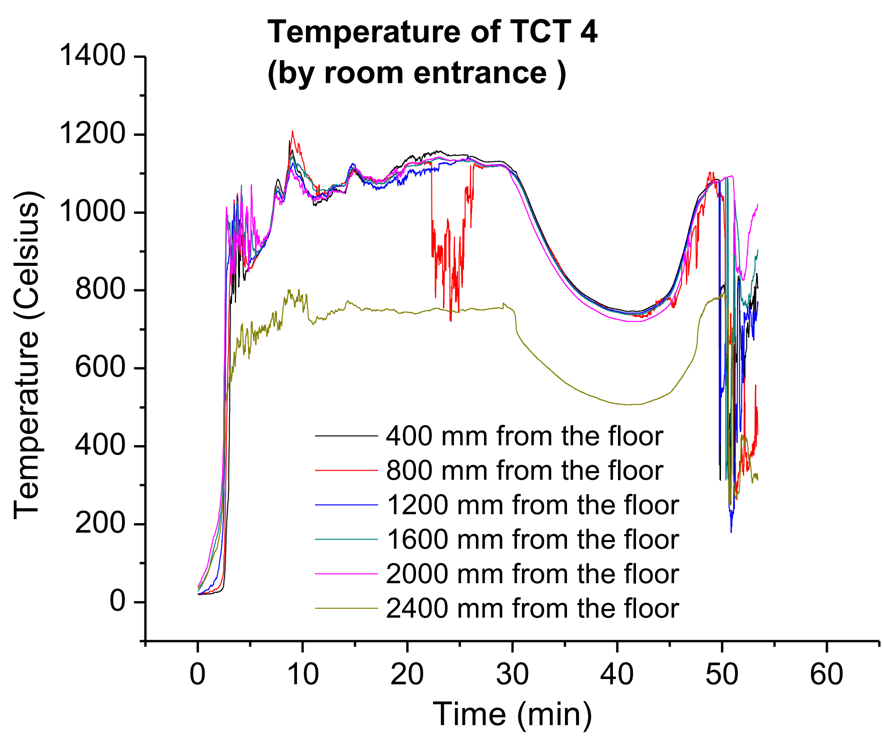

Figure 4-42: Room temperature recorded by thermocouple Tree 4

The thermocouples located closest to the ceiling at 2400 mm from the floor shows considerably lower temperatures for all four trees. The temperature in the room quickly rises after flashover and then it continues to rise slowly for about 18 minutes. The temperatures remain at about 1100^{o}C and then start to decay for about 20 minutes. At this point, both unprotected side walls were glowing with occasional flaming outbursts. The most affected portions of the side walls then started to delaminate allowing for additional fuel exposure. The room went into a second flashover and was immediately put out after that. A closer look at thermocouple Trees 3 and 4, Figure 4-41 and Figure 4-42, located at the room entrance, shows the abrupt drop in temperature due to the direct contact with the water.

4.2.4 Temperature of the CLT cross section

The temperature at the side walls was measured using embedded thermocouples. Similar to Test 1, wall thermocouple groups consisted of 6 thermocouples embedded at 3, 6, 9, 12, 15, 18, and 24 mm from the interior surface. The holes to embed the thermocouples were drilled from the outside of the room toward the inside. For this test, 4 thermocouple groups were used in each of the 2 unprotected side walls. The locations of the thermocouple groups were as follows. On the right side wall, Group 1 and 2 were located at 1.70 m from the floor. Group 1 was at 1.5 m from the entrance and Group 2 was located at 3.0 m from the entrance. Groups 3 and 4 were at a height of 0.85 m from the floor. Group 3 was at 1.5 m from the entrance and Group 4 was located 3.0 m from the entrance. On the left side wall, Groups 5 and 6 were placed 1.70 m from the floor. Group 5 was at 1.5 m from the entrance and Group 6 was located 3.0 m from the entrance. Groups 7 and 8 were located 0.85 m from the floor. Group 7 was 1.5 m from the entrance while Group 8 was located 3.0 m from the entrance. Figure 4-43 shows the location of the 4 thermocouple groups on the right wall. A similar instrumentation set up and spacing was used on the unprotected left side wall.

Figure 4-43: Relative location of embedded wall thermocouples

The temperature of each group varied according to their position in the room as well as in relation with the furniture distribution around them. Thermocouple Group 3 was behind the long dresser located near the right side wall while thermocouple Group 7 was next to the tall dresser located near the left side wall. Thermocouple Group 10 located 0.8 m from the floor along the center of the back wall was initially obstructed by the bed's headboard.

The cross section temperature of embedded thermocouple Groups 1 to 4 located on the right side wall is presented in Figure 4-44. Temperatures up to 350°C were plotted in the graph in order to focus on the initial stages of the fire and the heating behaviour of the cross section.

The temperature plateaus at around 100°C for a couple of minutes as the water in the panel is driven off as water vapour. Once the temperature at any point reaches 300°C, the wood is considered to be char. The last thermocouple of each group, embedded 24 mm into the wood, charred between 27 to 45 minutes into the test. In some cases such as in Group 3, there was a delay in charring.

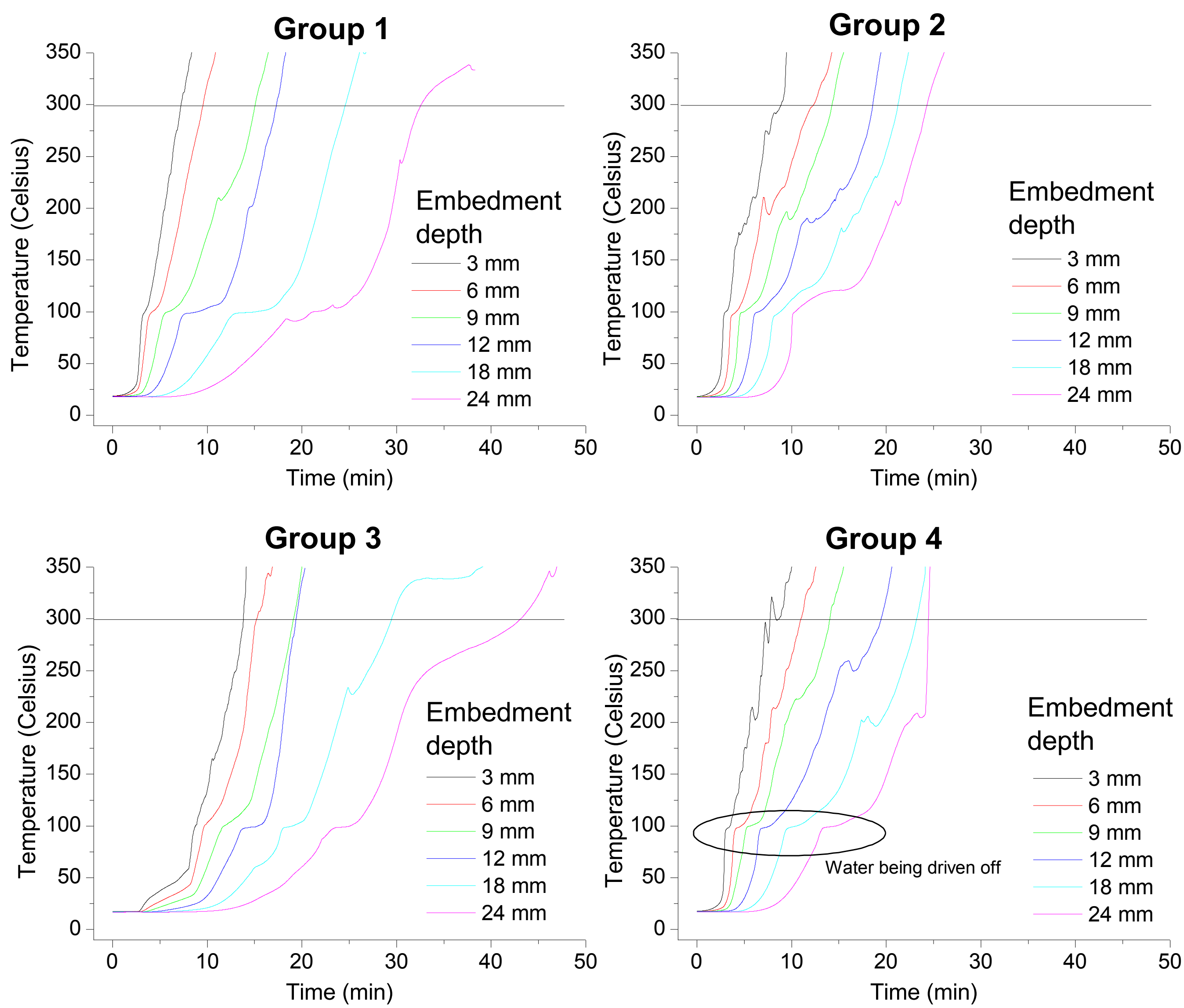

Figure 4-44: Temperature of embedded thermocouple groups on right side wall

Focusing on the first embedded thermocouple in all groups, located 3 mm from the interior surface in Figure 4-44 it can be seen that wall Groups 1 and 2, located 1.7 m from the ground and not obstructed by any furniture in the room reached a temperature of 300°C about 8 minutes from the start of the test. For wall Group 3, which is blocked by the long dresser, thermocouple 1 reaches a temperature of 300°C 13 minutes after room ignition. This represents a delay in charring of about 5 minutes for wall Group 3 because this group was not exposed to the high temperatures in the earlier stages of the fire.

Once the wood surrounding the thermocouple is consumed and the char layer is no longer offering any thermal protection, the exposed thermocouples start to measure the temperature of the room. Figure 4-45 illustrates an interesting behaviour on wall Group 4 at about 25 minutes. The temperature of all embedded thermocouples suddenly increased indicating that either the char layer had fallen off or that the first CLT ply had delaminated.

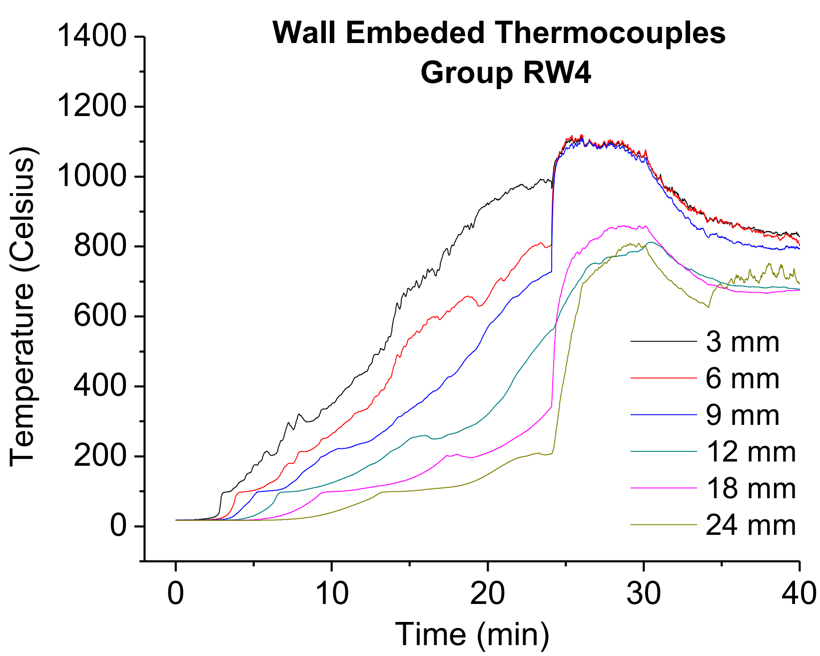

Figure 4-45: Temperature of thermocouples in Group 4. Bottom left of the right side wall.

Figure 4-46 depicts the cross-section temperature of the left side wall. Wall Groups 5 and 6 are located 1.7 m from the ground similar to Groups 1 and 2 on the right side wall. Groups 7 and 8 are located 0.8 m from the ground similar to Groups 3 and 4 on the right side wall. Group 5 and 7 are located 1.5 m from the front wall while Groups 6 and 8 are located 3.0 m from the front wall. The graphs pertaining to Group 6 and 8 in Figure 4-46 shows that the panels heat up much faster as the last embedded thermocouple (24 mm) chars before the 30 minutes mark. Groups 5 and 7, located closer to the entrance, char after a minimum of 35 minutes. These differences are due to uneven distribution of fuel as much of the furniture including the first ignited item (bed) were located in the back of the room.

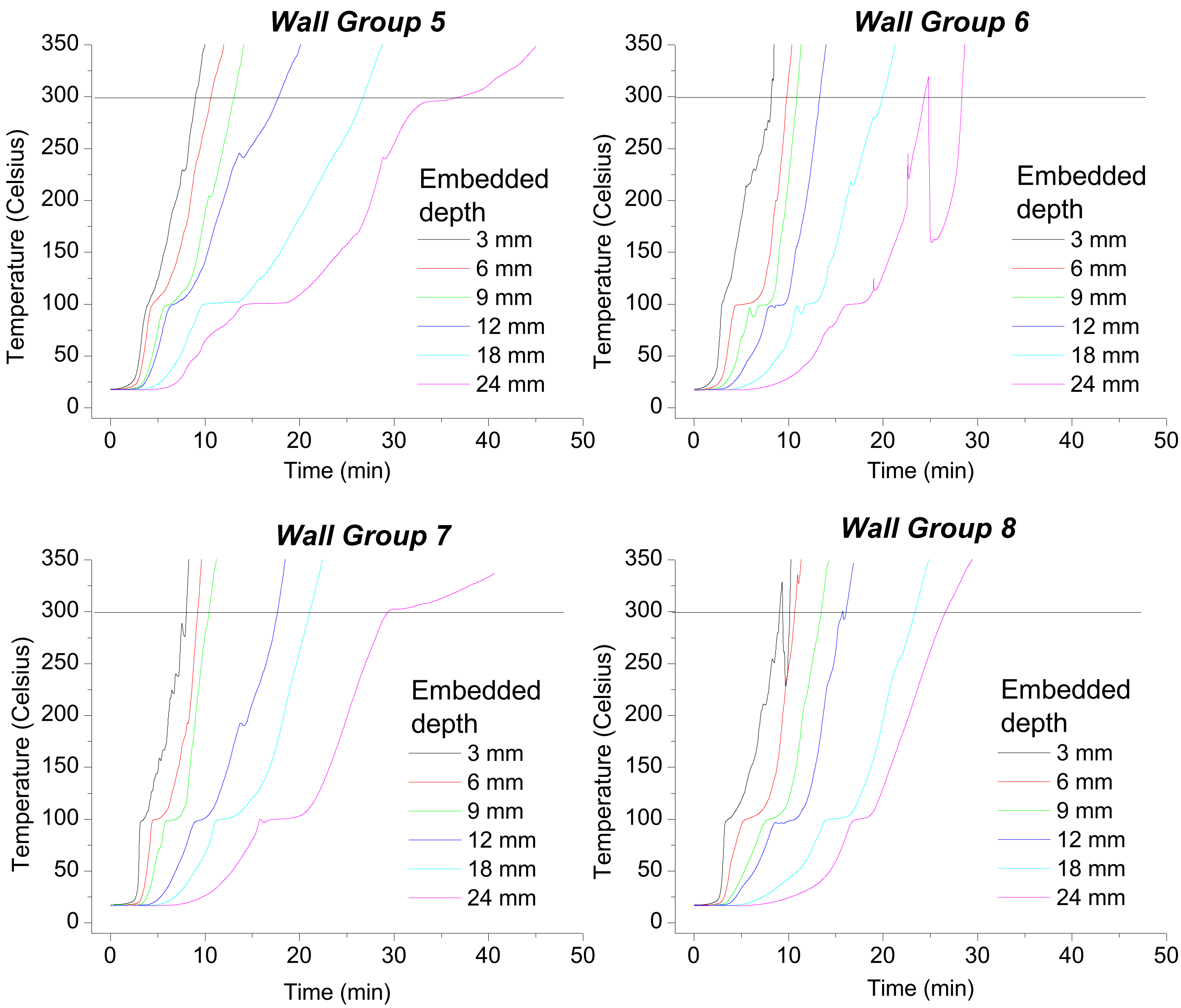

Figure 4-46: Temperature of embedded thermocouple groups on left side wall

The second room fire test failed the integrity criteria due to failure of the lap joints. As the left side wall was experiencing flaming out of the joint; it was decided to remove wall thermocouple Groups 5, 6, 7 and 8 to prevent damage of the cables. This occurred about 50 minutes into the test once all the thermocouples in these groups had reached 300°C.

The temperatures between the layers of gypsum board and between the gypsum board and the CLT surface are presented in Figure 4-47 and Figure 4-48. These temperatures were recorded on surfaces with 2 layers of gypsum board protection such as the ceiling and the back wall. The first thermocouple was embedded between the 2 layers of gypsum board protection. The second thermocouple was embedded between the last layer of gypsum board and the CLT panel. To measure the temperature of the protected CLT panels, a third thermocouple was embedded 6 mm from the CLT interior surface and was utilized to monitor if the panel would reach 300°C and therefore start to char.

Figure 4-47 shows the cross-section temperature of the rear wall. There were two embedded thermocouple wall groups used during this test. Wall Group 9 was located 1.7 m from the ground and wall Group 10 was located 0.8 m from the ground. Both groups were located along the center of the wall. The graphs for wall Group 9 and 10 show that the temperature between the second layer of gypsum board and the CLT surface never reached 300°C meaning the gypsum protection was adequate for 60 minutes allowing no charring of the wall panel.

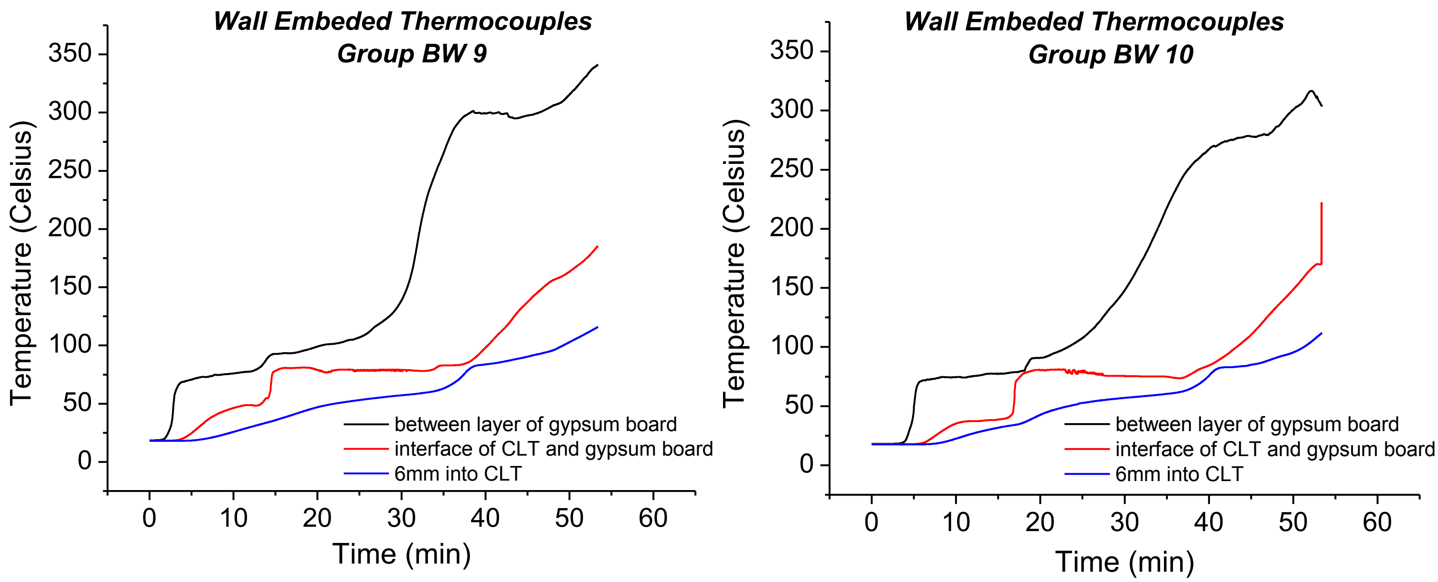

Figure 4-47: Cross-section temperature of protected rear wall during Test 2

Figure 4-48 shows the cross-section temperature of the ceiling assembly. There were two embedded thermocouple groups used to measure the temperature behaviour of the ceiling. Both groups were aligned along the center of the room. Group 1 was located 1.5 m from the front wall while Group 2 was located 3.0 m from the front wall. Group 1 shows a spike in temperature around 55 minutes into the test as the last layer of gypsum failed near the front of the room exposing the thermocouples to the fire.

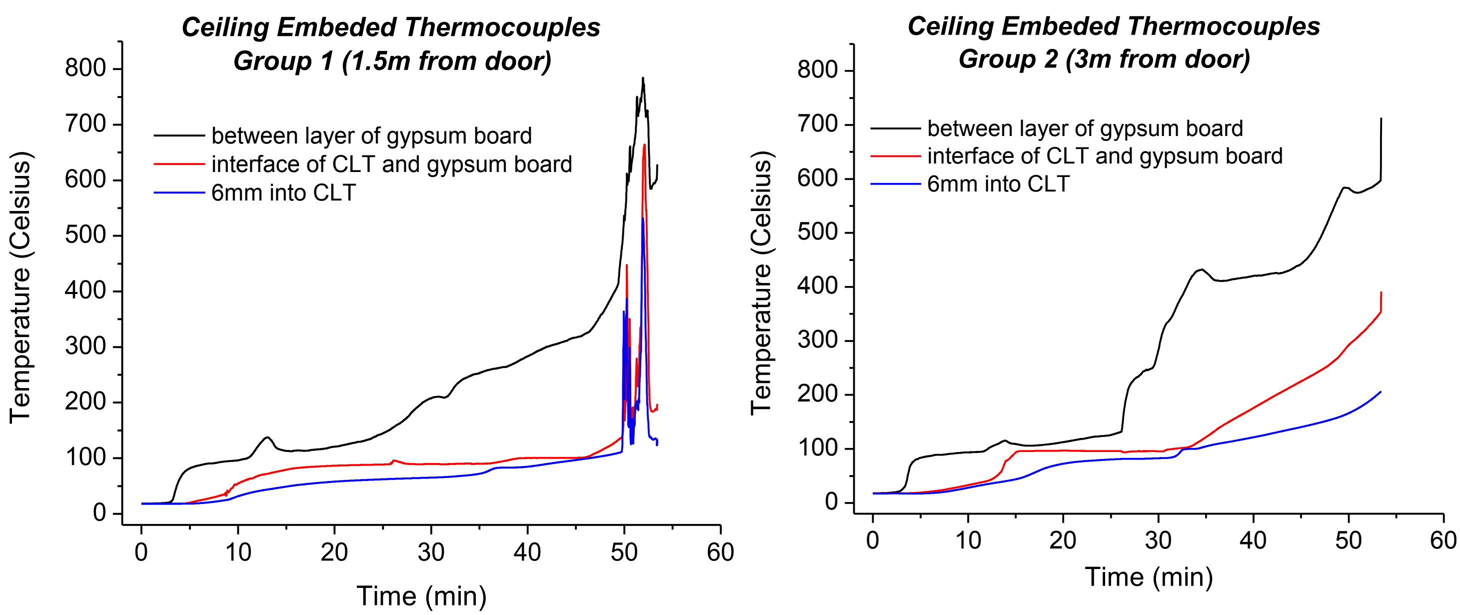

Figure 4-48: Cross-section temperature of protected ceiling during Test 2

Ceiling thermocouple Group 2 in Figure 4-48 shows the behaviour of gypsum board at high temperatures. As the outermost layer of gypsum board heats up and reaches 100^{o}C the chemically bound water starts to be driven off as water vapour. Once all the water in the first layer is driven off, the temperature in the second layer of gypsum board starts to increase and again it remains at 100^{o}C until all the water is driven off.

Temperature readings from thermocouple embedded 6 mm into the panel in Group 2 of the ceiling never reached 300^{o}C during the test therefore char did not reach this point. After the test, the measure char depth of the ceiling panels at most affected location was between 11 and 12 mm. The added char depth could be due to continued smouldering combustion long after the test was put out. Since the CLT panels could continue to burn after the fire is put out, calculations for charring rate were performed using only the data collected during the test at the predetermined embedded depths and not the final char depth of the panels measured after the test.

4.2.5 Charring depth / Remaining panel cross-section

The charring depth throughout the test of both side walls is presented in Figure 4-49. The time at which the embedded thermocouples in each group reach 300°C is recorded. These times together with the embedded depth of each thermocouple is graphed to show the movement of the char front at each location. Examining Figure 4-49, the char front at the top of the left wall towards the back (Group 6) moved the fastest while the bottom of the right wall (Group 3) close to the room entrance moved the slowest. This was the thermocouple group that was initially covered by the long dresser.

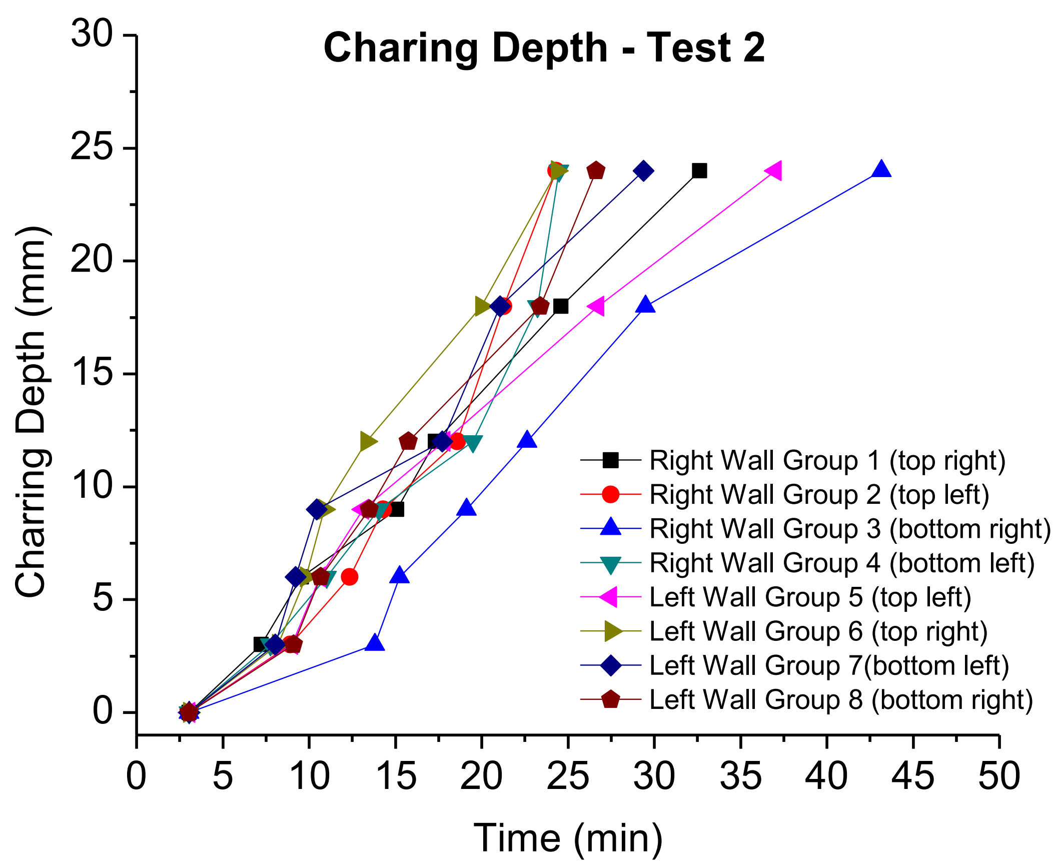

Figure 4-49: Wall panels charring depth during Test 2

The second test burned for a total of 57 minutes. Figure 4-50 shows the remaining cross section depth of the panel measured after the test. The initial cross-sectional thickness of the CLT panels was 105 mm. After approximately 1 hour of fire exposure with temperature never dropping below 700°C, panels 7 and 8 belonging to the protected back wall were barely charred. Panels 1 and 2 from the front wall had higher charring depths due to the constant impinging of flames exiting through the door opening.

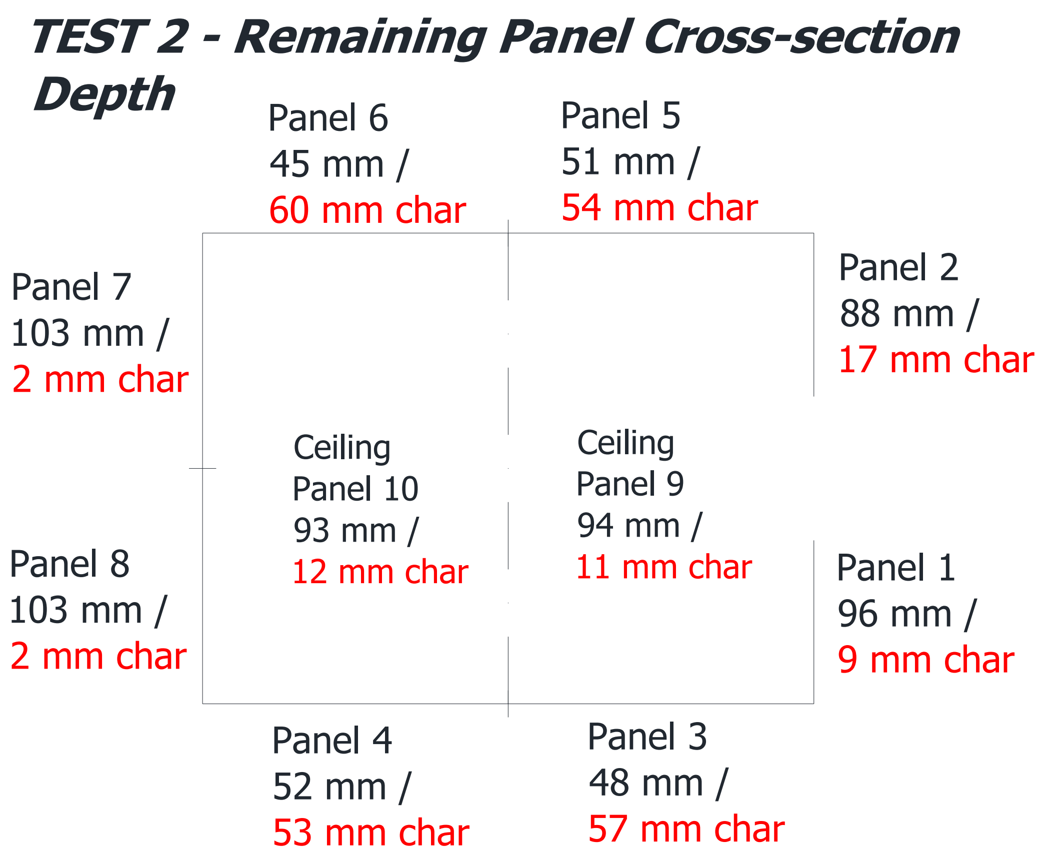

Figure 4-50: Plan view sketch of remaining cross-section thickness of CLT wall and ceiling panels after Test 2

4.2.6 Charring rate

Similarly to Test 1 the charring rate of the unprotected CLT wall panels was calculated at multiple positions using the average charring method as explained in room Test 1. Figure 4-51 shows the four graphs pertaining to the charring rate of the right wall. The point of reference for the locations specified on the graphs is from the interior of the room facing the specified wall. Groups 1, 3 and 4 have a charring rate average of 0.8 mm/min while Group 3 has an average charring rate of 0.6 mm/min. The charring rate of Group 3 is lower than the other groups because of the initial obstruction of the long dresser at this position in the room.

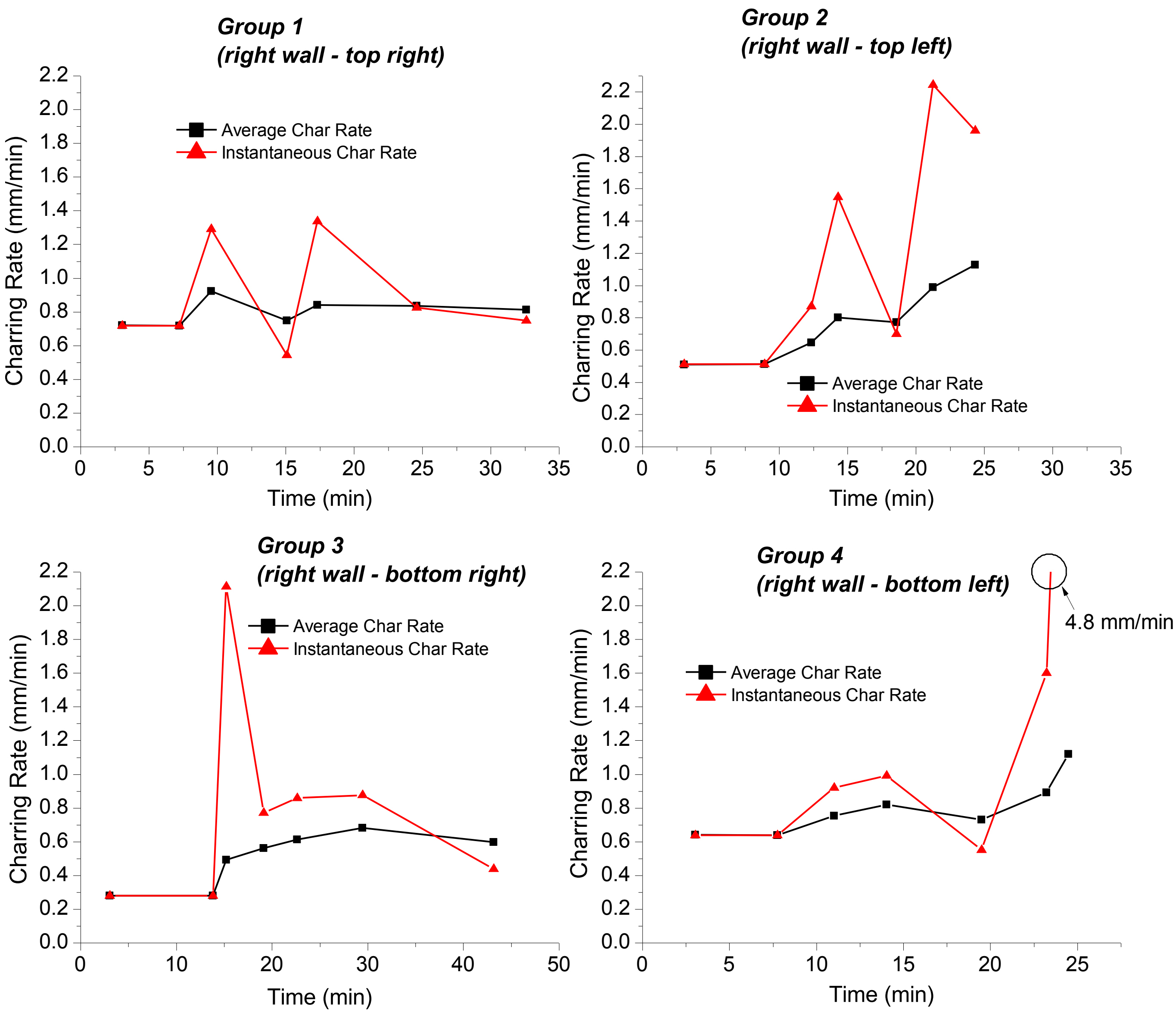

Figure 4-51: Charring rate at 4 locations in the right side wall

The charring rate for 4 different locations in the left side wall is presented in Figure 4-52. The charring rate on the four groups appears to start around 0.6 mm/min at the beginning of the test but quickly increased to just over 1.0 mm/min. The overall charring rate during the test was above the average theoretical value of 0.65 mm/min. The reasoning for this high charring rate could be that the HRR and temperature in the room never decreased once the room contents had been consumed. Instead, the exchange of gases through the wall joints as well as early ply delamination allowed the fire to continue with temperatures never dropping below 700°C.

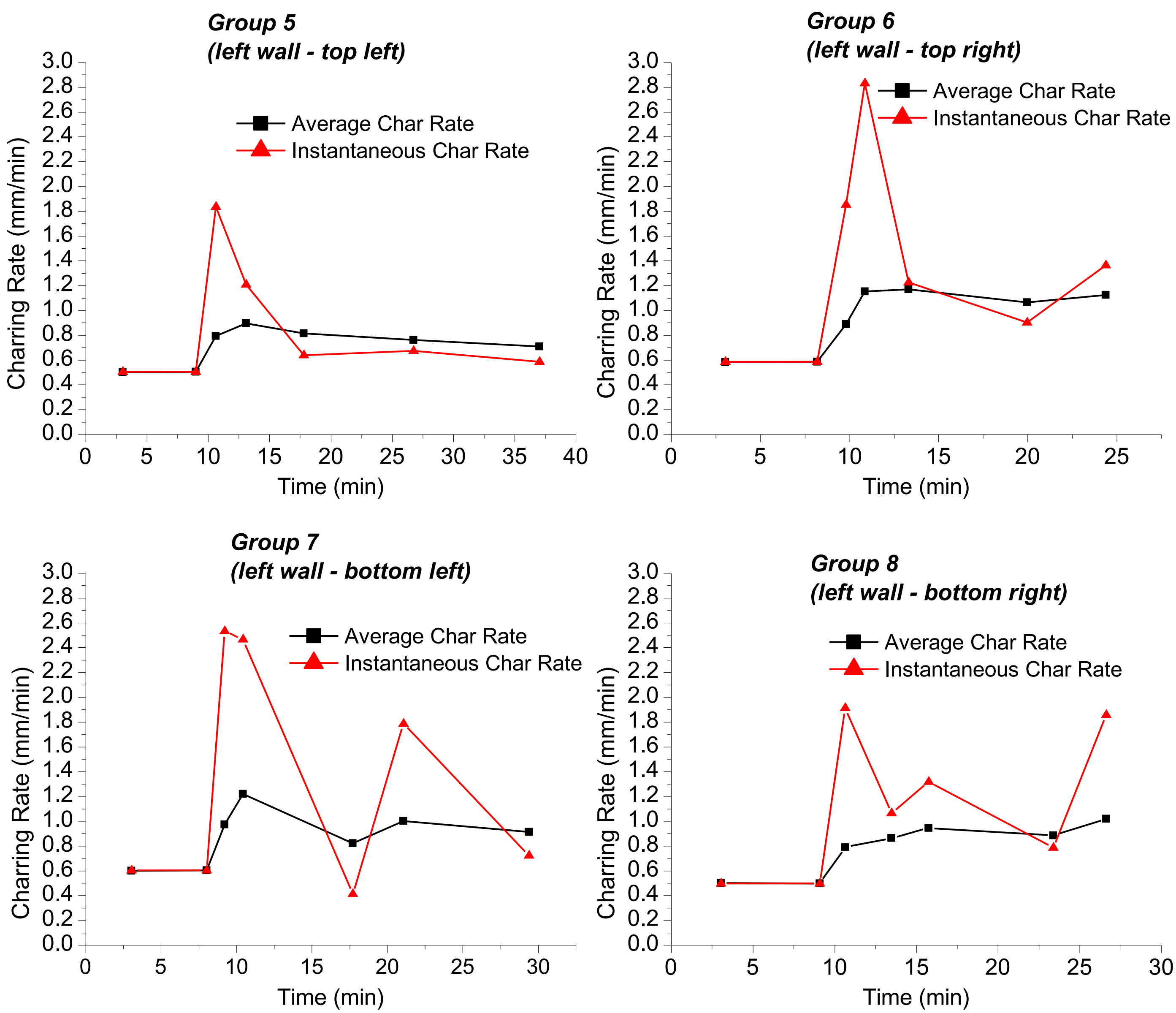

Figure 4-52: Charring rate at four locations in the left side wall

4.3 Test 3 - Unprotected Right Side Wall, other Interior Surfaces Protected

Test 3 was conducted on the morning of July 4, 2013. After the first two tests failed to self-extinguish after the room contents had been consumed, it was decided to reduce the area of unprotected CLT. It was decided to keep one of the side walls unprotected as it had a greater area. The area of the unprotected wall was 11.25 m^2 which is 29.7% of the total wall surface area in the room or 16.2% of total surface area of the room counting floor and ceiling. For both percentage calculations, the area of the door open is not included in the area of the front wall as previously done for Test 1 and Test 2.

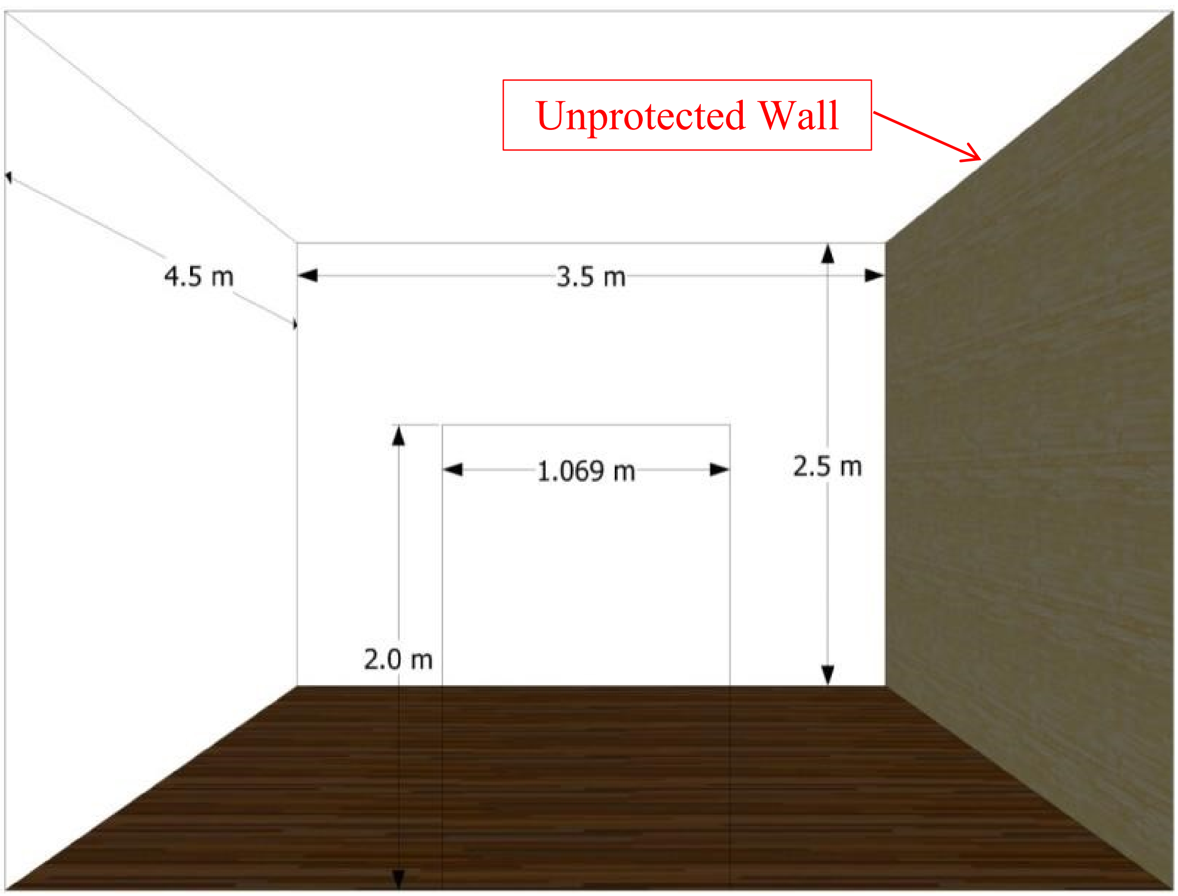

Figure 4-53: Test 3 interior room dimensions.

Figure 4-53 shows a sketch of the room containing the interior dimensions as well as the protected and unprotected wall panels of Test 3. The dimensions of the door opening, the width, length and height of the room were kept the same as the previous two tests. The room was manually ignited by the lab technician using a propane burner at 11:16AM. The temperature of the room at the time of ignition was 22^{o}C measured by the thermocouple trees. Throughout the length of the test all three exhaust fans in the facility were operating at 75% of their maximum capacity similarly to Test 1 and 2. The moisture content of the unprotected CLT wall was measured at 4 separate locations for an average of 14%

4.3.1 Description of the test

The first ignited item in the room was the pillow located on the right side of the bed, Figure 4-54. A minute later the entire pillow was burning and fire had spread to the bed cover. Two minutes into the test lots of black smoke started exiting the room. At 11:19AM the entire bed was on flames and material from the covers was dripping onto the floor. As the fire gained strength, a dense layer of smoke started to accumulate near the ceiling and visibility into the room was very poor. In order to better predict the time of flashover, a couple of scrap paper balls were used to observe the spontaneous combustion, Figure 4-55. At 11:20 AM, 4 minutes from ignition, the paper balls ignited indicating flashover had occurred in the room. Large flames started to exit the room through the door.

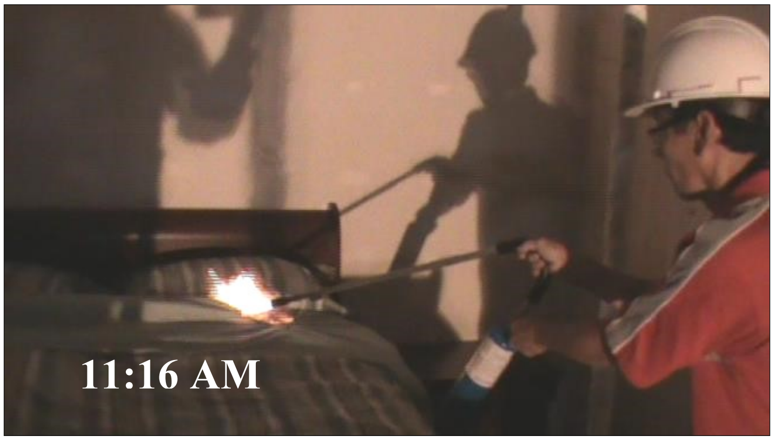

Figure 4-54: First ignited item. Right pillow

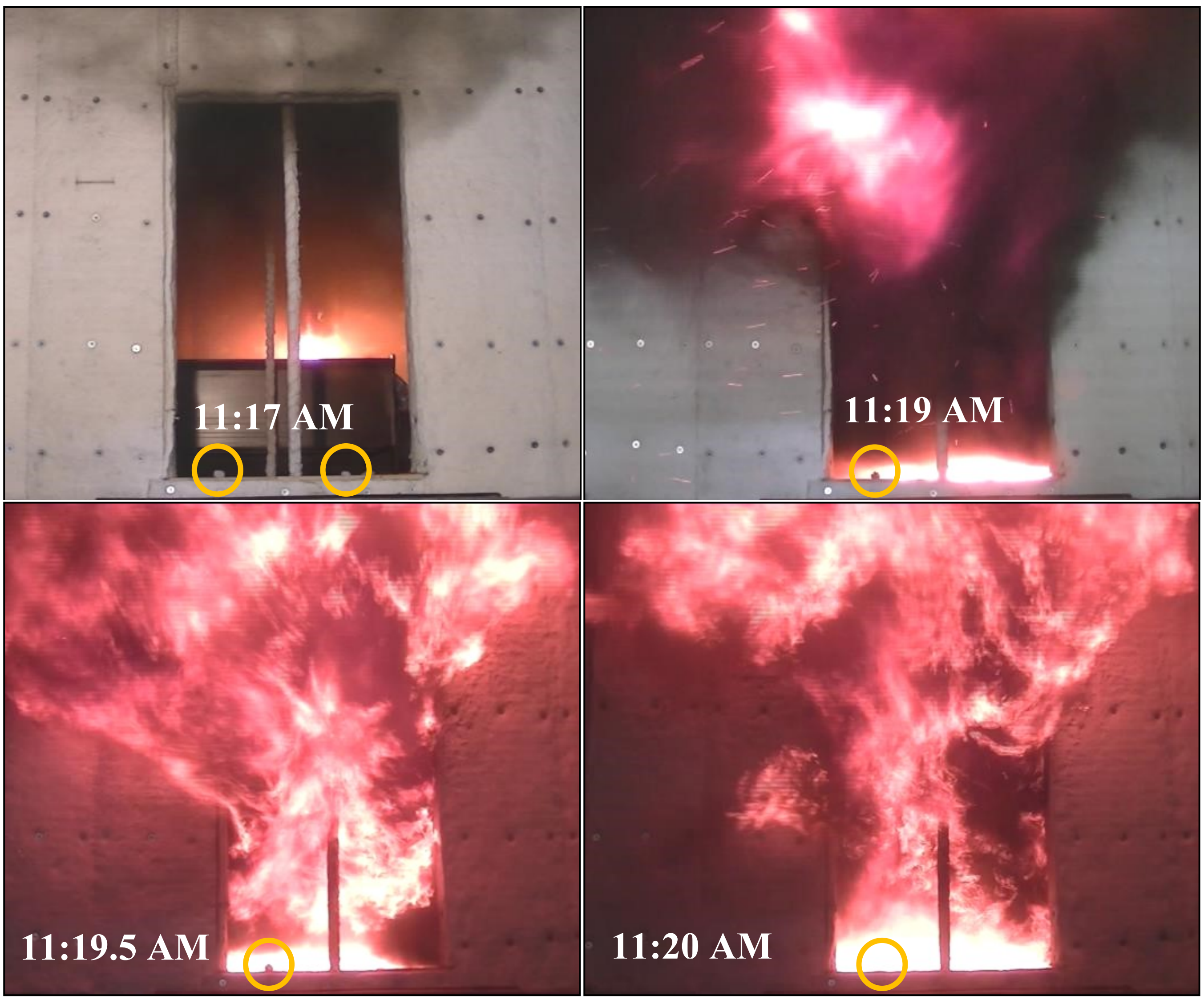

Figure 4-55: Fire growth early in the test. Paper balls used to better detect room flashover.

The first layer of gypsum board protection on the back wall failed after 25 minutes of exposure to the fire. At 11:43AM, 27 minutes into the test, an explosion like behavior occurred on the unprotected wall. Spurs of gases and glowing particles were being launched from within the char layer and landing in the middle of the room. The underneath of the char layer was seen glowing red.

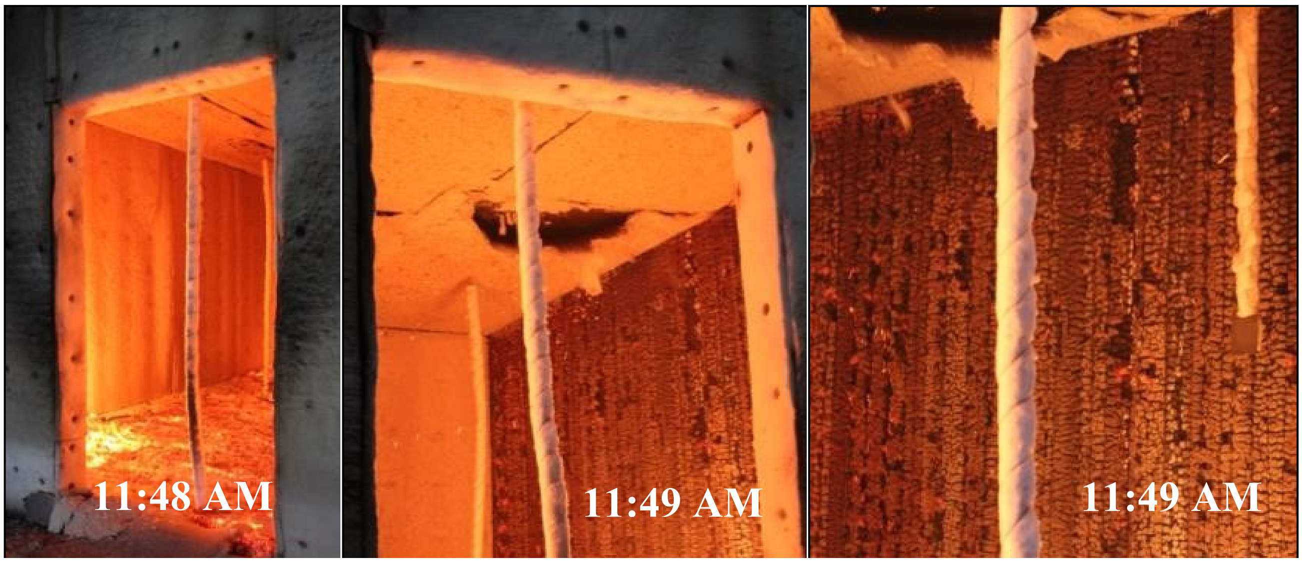

Figure 4-56: Fall-off of gypsum board on the ceiling

The first layer of the gypsum board on the ceiling at the front of the room near the entrance failed after 33 minutes of exposure at 11:49 AM, Figure 4-56. The temperature kept dropping until it reached 161°C on the plate thermometer at 12:36 PM at which point it was decided to extinguish the room, Figure 4-58. As Figure 4-57 shows the room was smoldering at this time with no signs of reigniting.

Figure 4-57: Room Test 3 smouldering at the end of a 80 minutes test

Figure 4-58: Room Test 3 is manually extinguished

4.3.2 Heat release rate

The heat release rate measured during Test 3 is illustrated in Figure 4-59. Both HRR and temperature curves behave similarly as they are interdependent. The maximum HRR recorded during Test 3 was about 4 MW which happened around the same time at which the maximum temperature occurred. During the decay phase of the fire, the HRR decreases significantly faster than the temperature due to the unavailability of fuel to burn. The temperature in the room takes longer to cool due to radiation of the burned objects that remain hot specially the smouldering unprotected wall and furniture ashes.

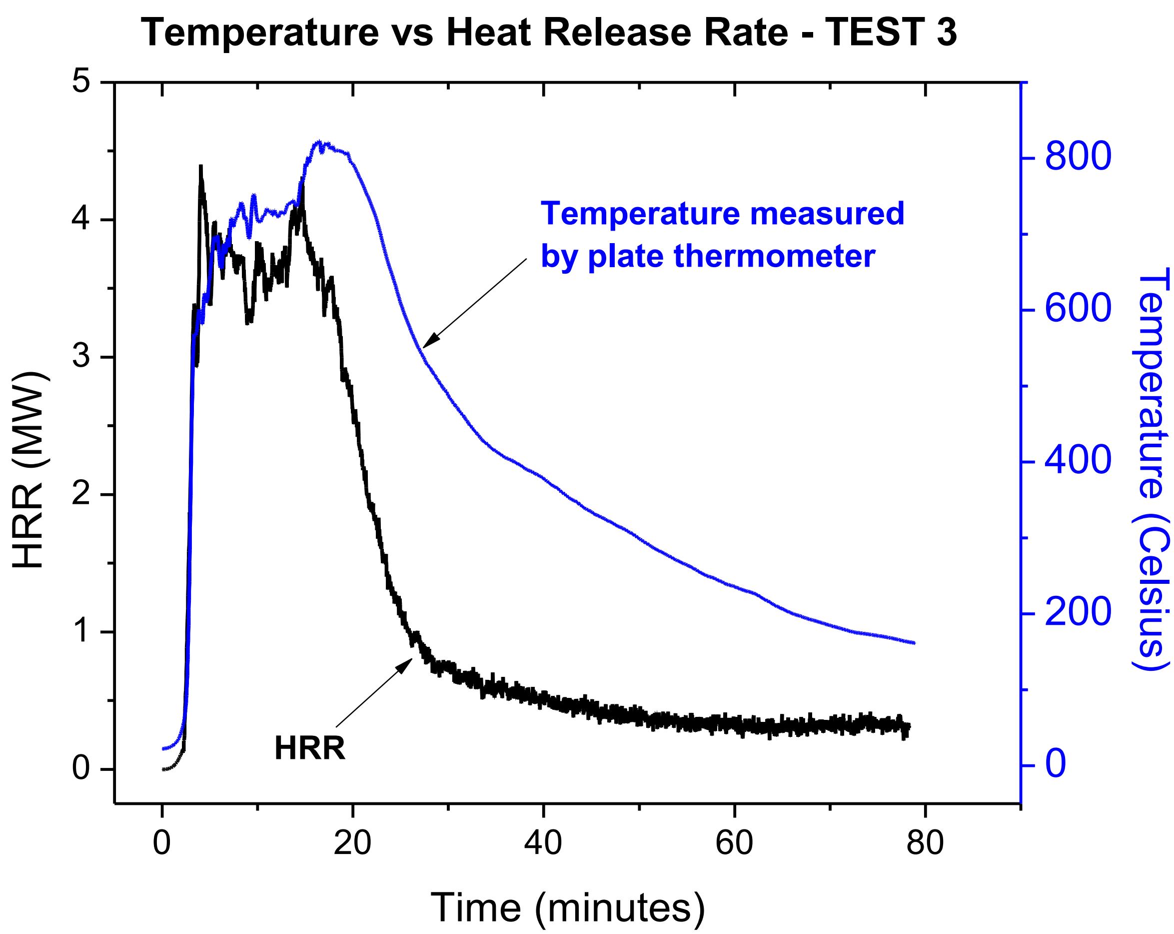

Figure 4-59: Temperature and HRR output during room Test 3

4.3.3 Temperature in the room

The temperatures of the room are shown in Figure 4-60. The figure presents the average of the temperatures recorded by each of the 4 thermocouple trees as well as the temperature of the plate thermometer throughout the test. The rapid increase in temperature at 4 minutes is indicative of flashover. The plate thermometer recorded temperatures similar to those measured by thermocouples in Trees 3 and 4. The maximum temperature measured by the plate thermometer was 823°C immediately after room flashover. As the room kept burning, it reached a maximum temperature of 1097°C recorded by thermocouple Trees 1 and 2 (back corners of the room) 20 minutes after ignition. Thermocouple Trees 1 and 2 had relatively higher temperatures throughout the test. Thermocouple Trees 3 and 4 reached a maximum temperature of 777°C, and 757°C respectively.

The fire reached the decay phase 20 minutes after ignition. After this time, the temperature kept decreasing as the fire was decaying. It should be noted that the CLT used to build this room was manufactured by Structurlam Innovative Wood Specialists and not Nordic Engineered Wood as in the first 2 room tests. There was one major physical difference between the types of CLT panels. Although the overall thickness of each ply was the same at 35 mm, the boards from Structurlam were manufactured wider. A wider board has a greater area of contact meaning more adhesive per plank, fewer planks per ply and ultimately less plank to plank joints. In addition to having less exposed CLT surface area during Test 3, wider planks in the CLT panels might have contributed to less ply delamination. The unprotected right wall in Test 3 was not subjected to radiation from the left wall as was the case for Test 2. The lack of radiation meant that the temperature of the right wall during Test 3 was not as high as it was for Test 2.

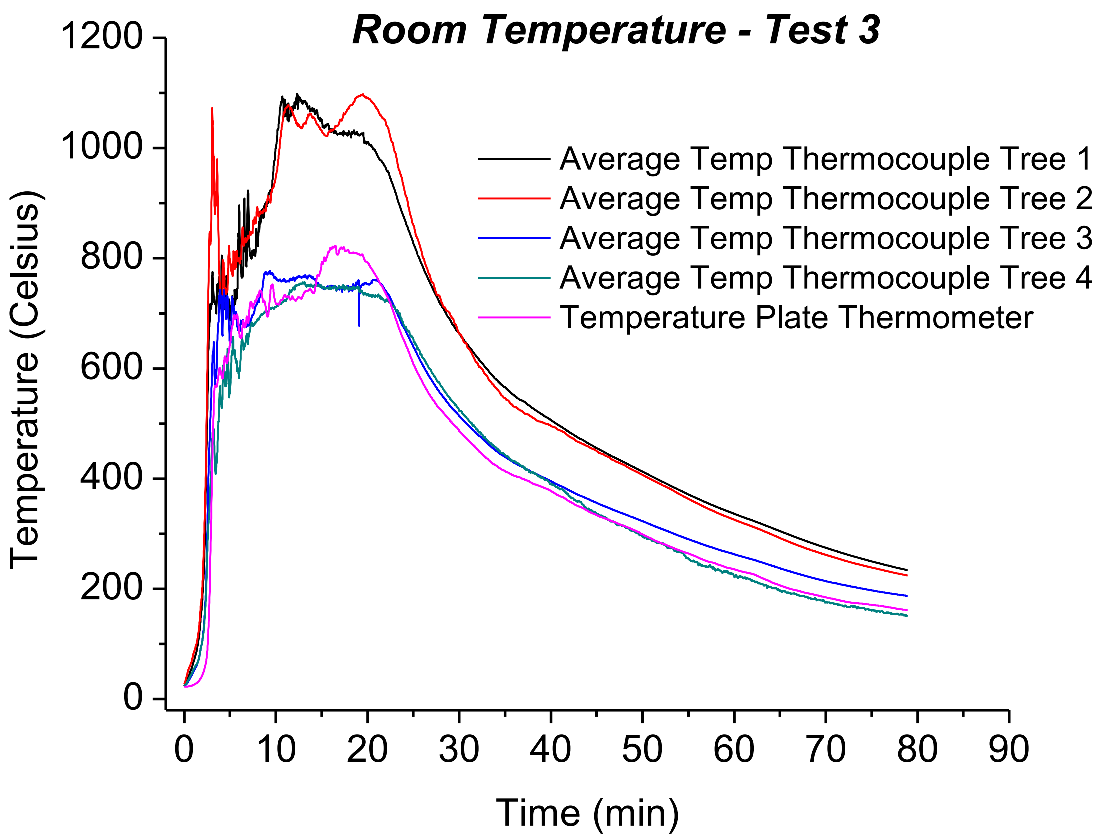

Figure 4-60: Test 3 room temperature measured by thermocouple trees and plate thermometer

The behaviour of the fire throughout the first couple of minutes is displayed in Figure 4-61 below. The fire quickly progressed from burning locally in the bed to full flashover in about 4 minutes. After flashover there was a production of a lot of black smoke and flames were exiting the compartment signifying a ventilation control fire.

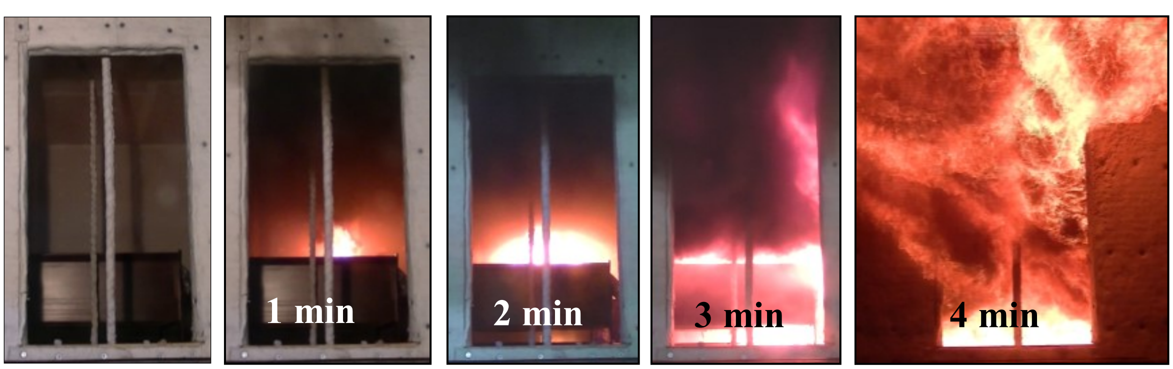

Figure 4-61: Fire progression during the first few minutes of the test

Unlike Test 1 and 2, the fire did not regain its strength after the contents had been consumed. The unprotected CLT wall did not delaminate prematurely. This allowed the first layer of the panel to char completely maintaining the char depth which served as thermal insulation.

The temperature measured by all thermocouple trees was characterized by a similar behaviour. Initially the temperature rises quickly and then it briefly plateaus and finally it goes into a long and steady decline. Figure 4-62 to Figure 4-65 show the temperatures recorded by each thermocouple tree during Test 3. There is no noticeable difference between the temperatures recorded at the bottom or near the top of the room. This indicates good mixing of the hot gases in the room as flames were engulfing all room combustible surfaces including the floor. The major difference is the maximum temperatures recorded by each tree. Although the maximum temperature occurred at the same time, thermocouple Trees 1 and 2 recorded an average of 350°C higher than thermocouple Trees 3 and 4. The reason for this difference in temperature could be that the fire was started at the bed near the back of the room. The foam mattress tends to burn very vigorously and fast creating spikes in temperature for nearby measuring devices such as thermocouple Tree 1 and 2. This difference in temperature was not seen during Test 1 and 2 although the location of the thermocouple trees in Test 3 was the same as in Test 1 and 2.

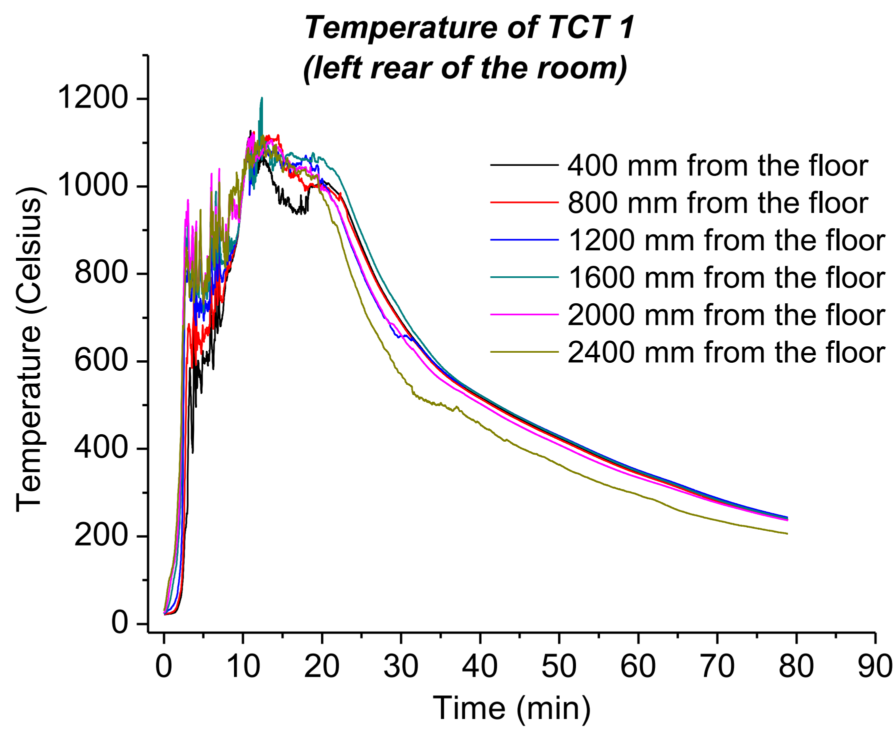

Figure 4-62: Temperature recorded by thermocouple Tree 1 during room Test 3

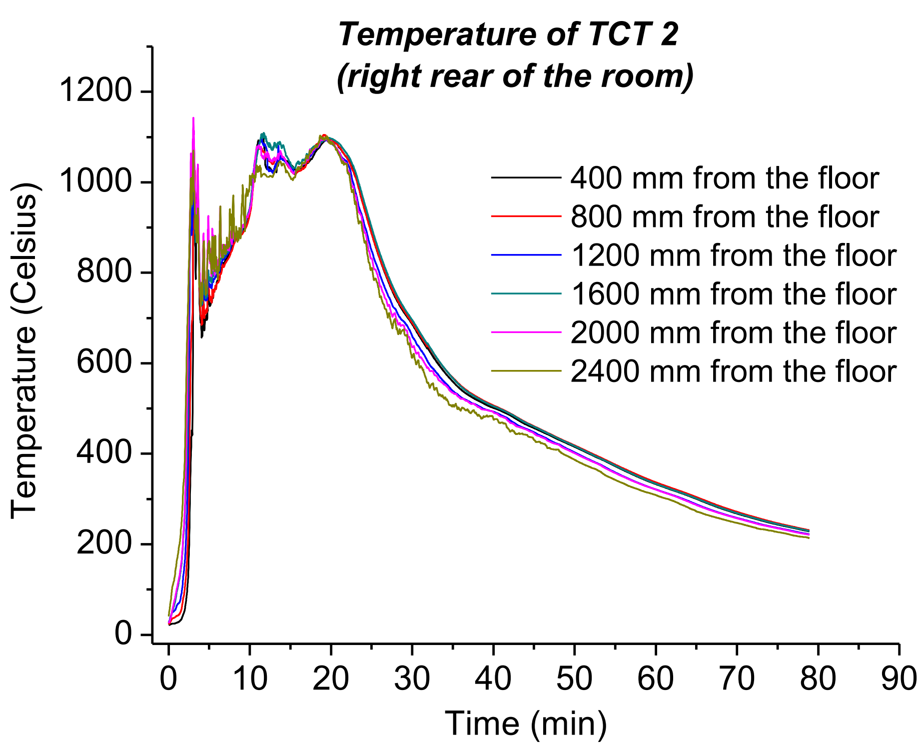

Figure 4-63: Temperature recorded by thermocouple Tree 2 during room Test 3

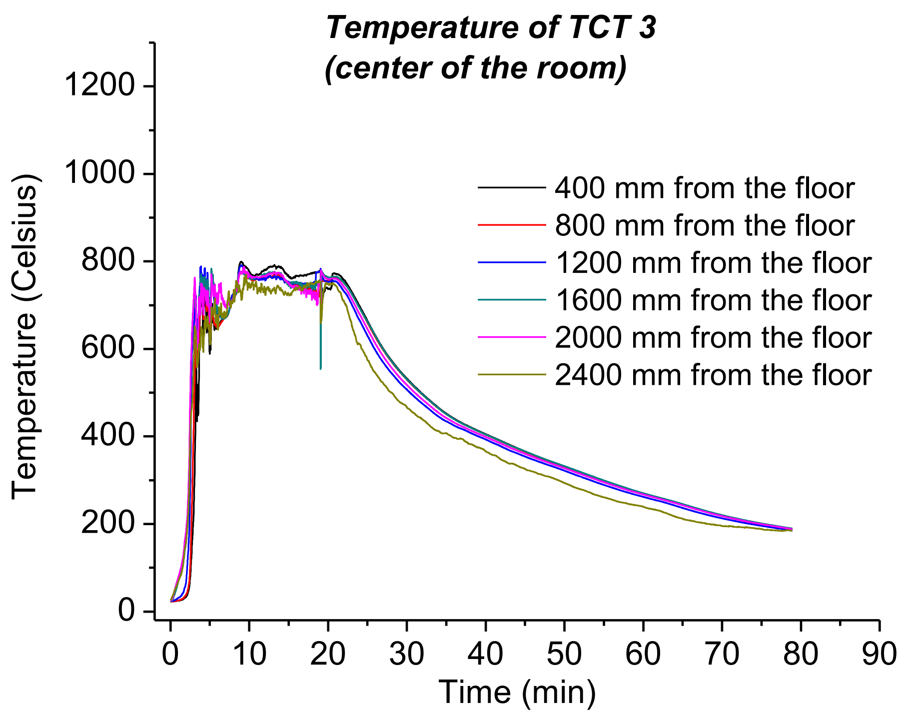

Figure 4-64: Temperature recorded by thermocouple Tree 3 during room Test 3

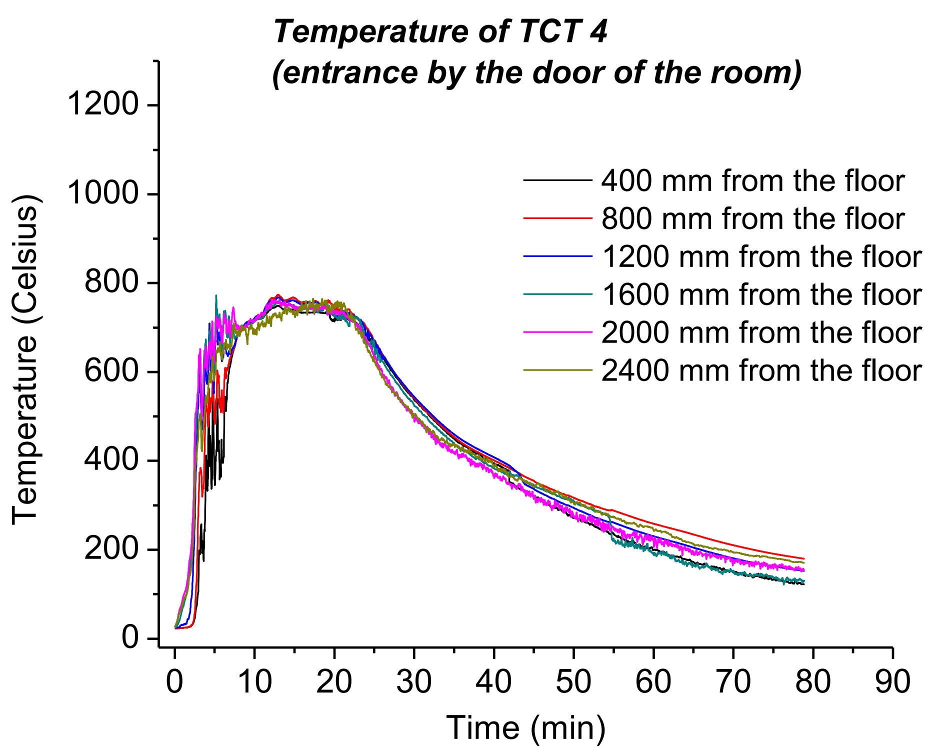

Figure 4-65: Temperature recorded by thermocouple Tree 4 during room Test 3

4.3.4 Temperature of the CLT panels

To measure the temperature within the unprotected wall, it was decided to utilize 6 embedded thermocouple wall groups similar to Test 1. Given that only one CLT wall was unprotected during this test; it was decided to increase the number of thermocouple groups used to get more data to investigate the process of thermal penetration into the panel and consequently charring. The thermocouple groups located on the unprotected right wall were embedded at 3, 6, 9, 12, 18, and 24 mm from the interior surface of the room. Groups 1 and 2 were located 1.8 m from the ground while Groups 3 and 4 at 1.2 m and Groups 5 and 6 at 0.6 m from the ground. Groups 1, 3, and 5 were located 1.5 m from the front wall while Groups 2, 4, and 6 were located 3.0 m from the front wall.

The thermocouple groups located on the rear wall and the ceiling were embedded between the 2 layers of gypsum board, at the CLT-Gypsum interface, and one 6 mm into the panel. Group 7 was positioned 1.6 m from the floor while Group 8 was located 0.8 m from the floor. Both groups were aligned along the center of the wall. Figure 4-66 shows the temperature of the 6 embedded thermocouple groups on the right side wall. The temperature of the 2 embedded thermocouple groups on the rear wall and ceiling are shown in Figure 4-67

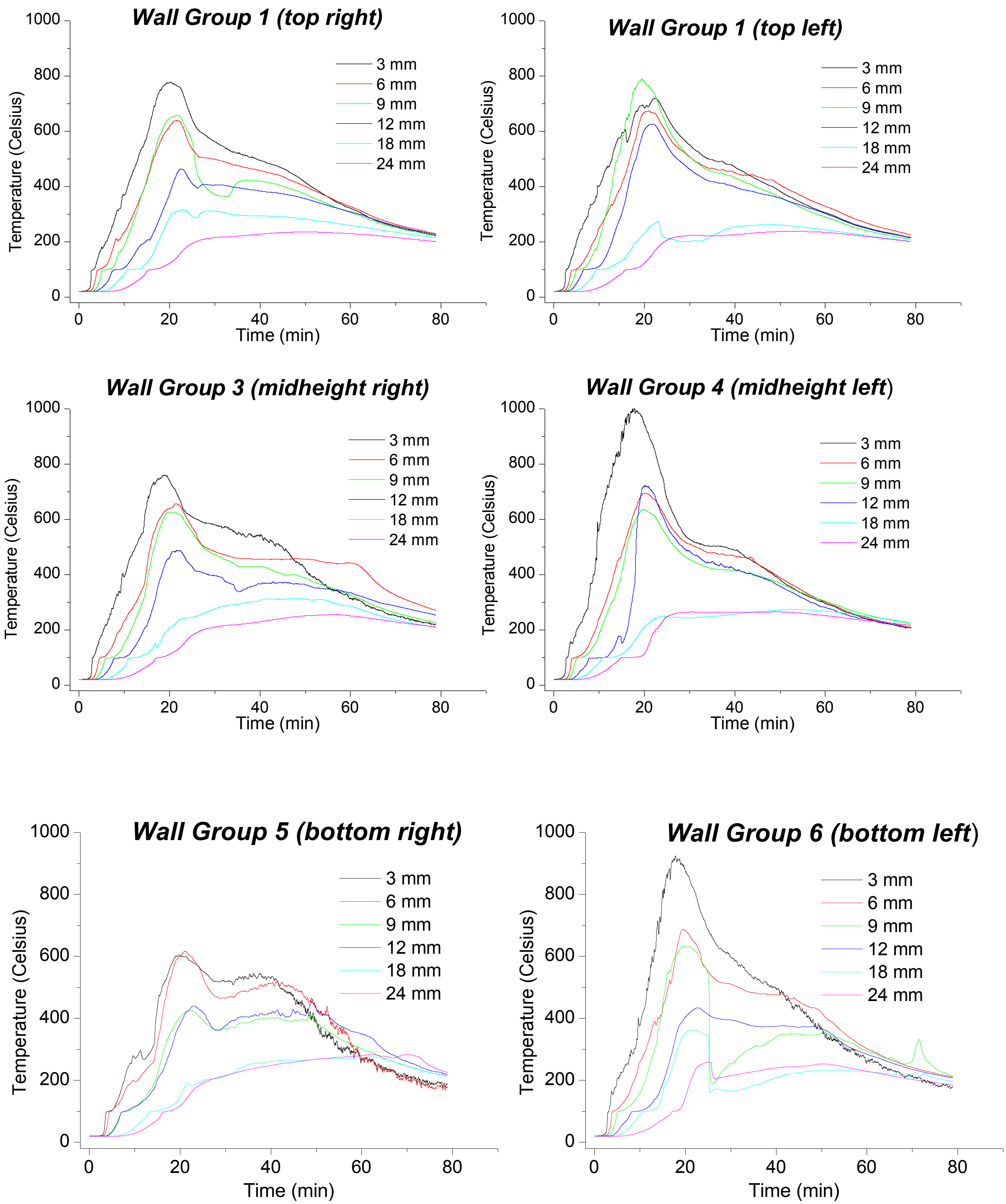

Figure 4-66: Temperature of embedded thermocouple groups on the right side wall

The temperatures recorded by thermocouple Groups 1 through 6 located on the unprotected wall were very similar with few exceptions. Groups 1, 2 and 3 recorded a maximum temperature of about 820˚C. These groups were located away from the bed of the fire and therefore experience lower temperatures at the beginning of the test. Groups 4 and 6 recorded a maximum temperature of nearly 1000˚C. These two groups were located near the far right corner of the room where the fire was ignited. Finally, thermocouple Group 5 reached a maximum temperature of about 600˚C due to the initial blockage of the wall by the long dresser. These temperatures were all read from the thermocouple closest to the surface of the room which was embedded at 3 mm from the interior surface and was the first to be exposed to the room temperature

Due to the steady decrease in temperature once the furniture was consumed and given that the unprotected CLT self-extinguished, thermocouples embedded at 18 and 24mm form the interior surface in all thermocouple groups did not reached 300˚C, therefore did not char. Also noted is the flattening of the temperature experienced by all the embedded thermocouples at around 100˚C due to water evaporation in the panel. The temperature of the protected rear wall as well as the ceiling was also recorded to monitor gypsum board fallout as well as heat penetration underneath these layers of protection. Figure 4-67 illustrates the temperature behaviour of the rear wall and the ceiling throughout the test.

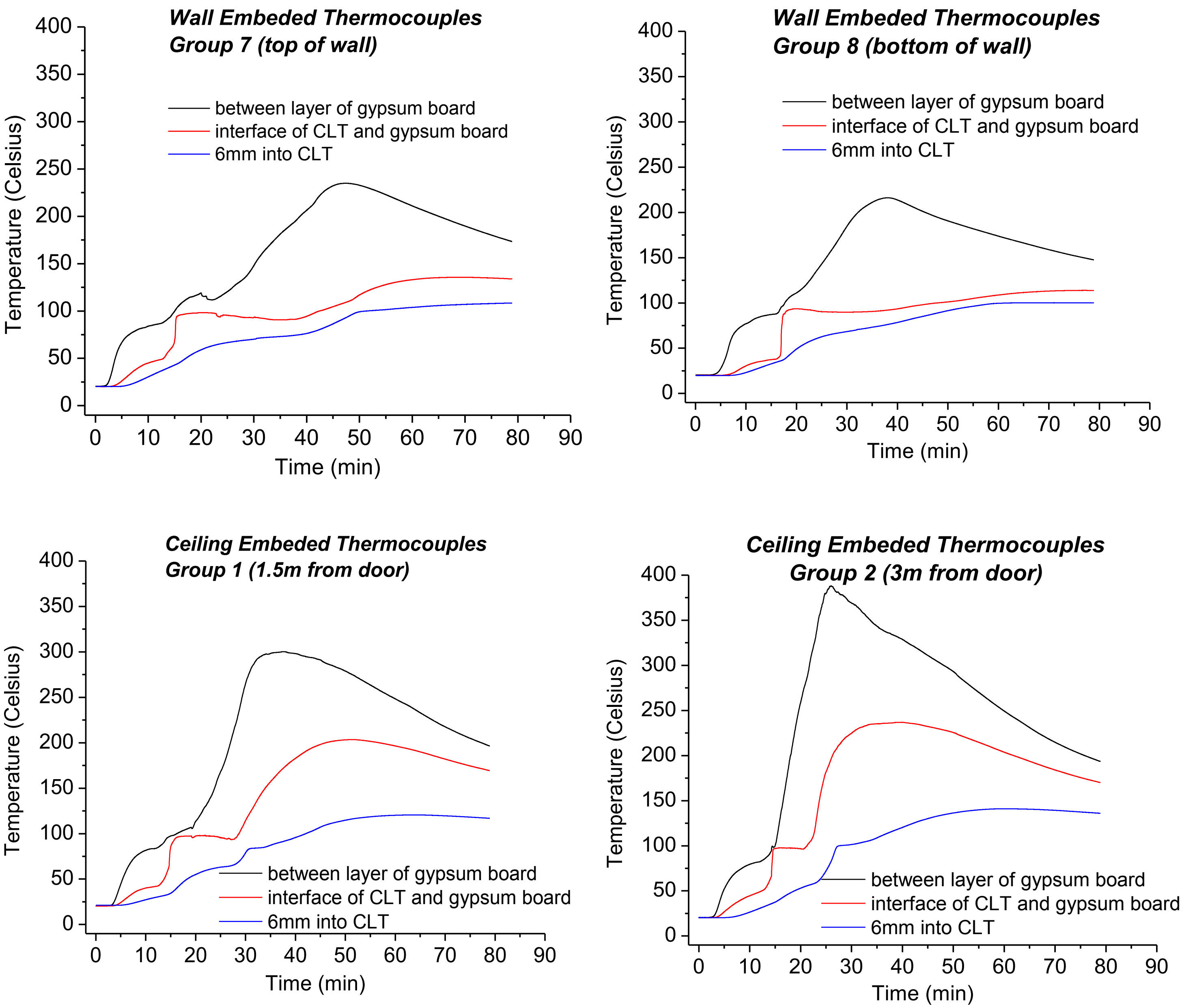

Figure 4-67: Temperature of embedded thermocouple groups on rear wall and ceiling

Similarly to the thermocouples embedded on the unprotected wall, the temperature readings levelled off at 100˚C but remained at that temperature for a longer period of time due to a greater amount of chemically bonded water in gypsum compared to water in the wood. On the rear wall, the temperature of thermocouples behind the first layer of gypsum board reached a maximum value of 230°C. The maximum temperature between the two layers of gypsum board in the ceiling was 385°C which occurred 26 minutes into the test. The maximum temperature between the second layers of gypsum board and the CLT panel was 235°C and at 6 mm into the wood the maximum temperature was 140°C.

4.3.5 Charring depth / Remaining panel cross-section

The movement of the char front through the CLT panels during Test 3 is shown in Figure 4-68. Since only one CLT wall was unprotected in this test and the wall did not have a major contribution to the combustion process with no ply delamination, the char front moved slower than in room Test 1 and 2.

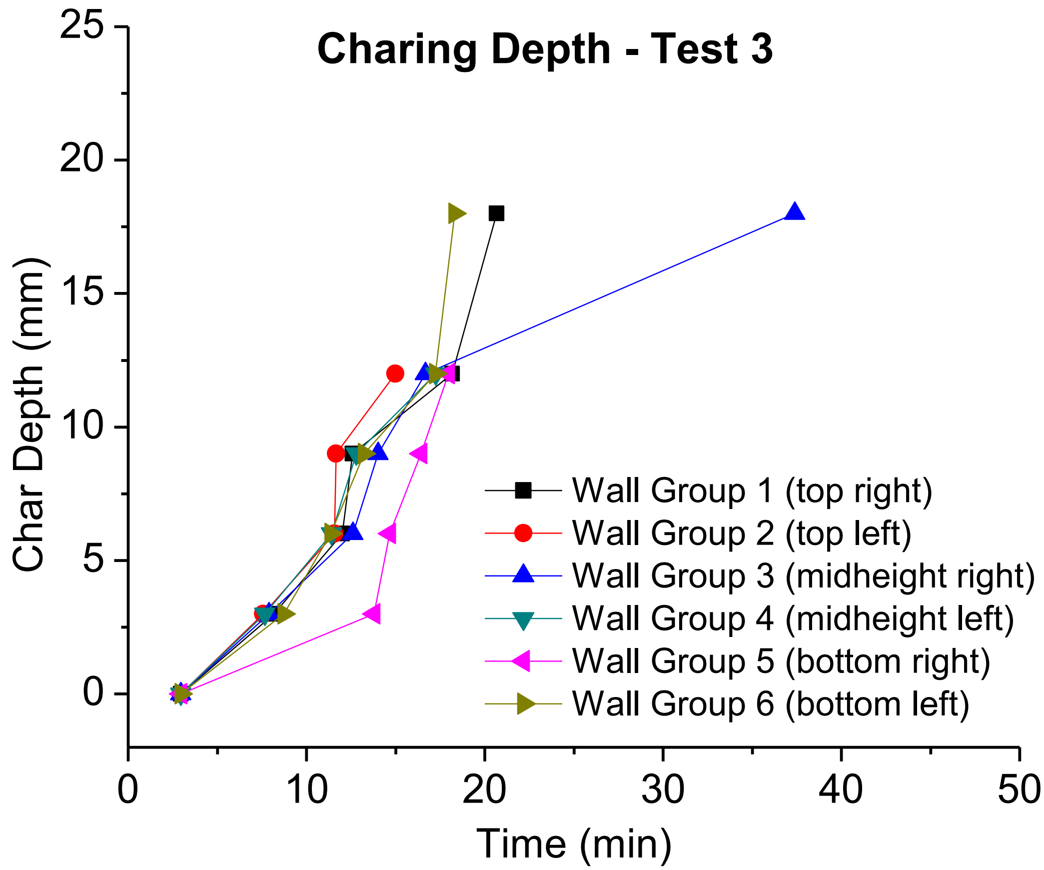

Figure 4-68: Wall panel charring depth at six locations during Test 3

The room burned for a total of 80 minutes. Once the furniture was consumed the temperature in the room decreased steadily without contribution of the unprotected CLT wall. At least one layer of gypsum board remained in place on all originally protected surfaces. Given the protection provided by the gypsum board, none of the panels other than the unprotected CLT wall experienced any charring. Figure 4-69 shows the remaining cross-section depth of all the CLT panels in the room. Similarly to room fire Test 1 and 2, the initial cross-sectional thickness of the CLT panels was 105 mm.

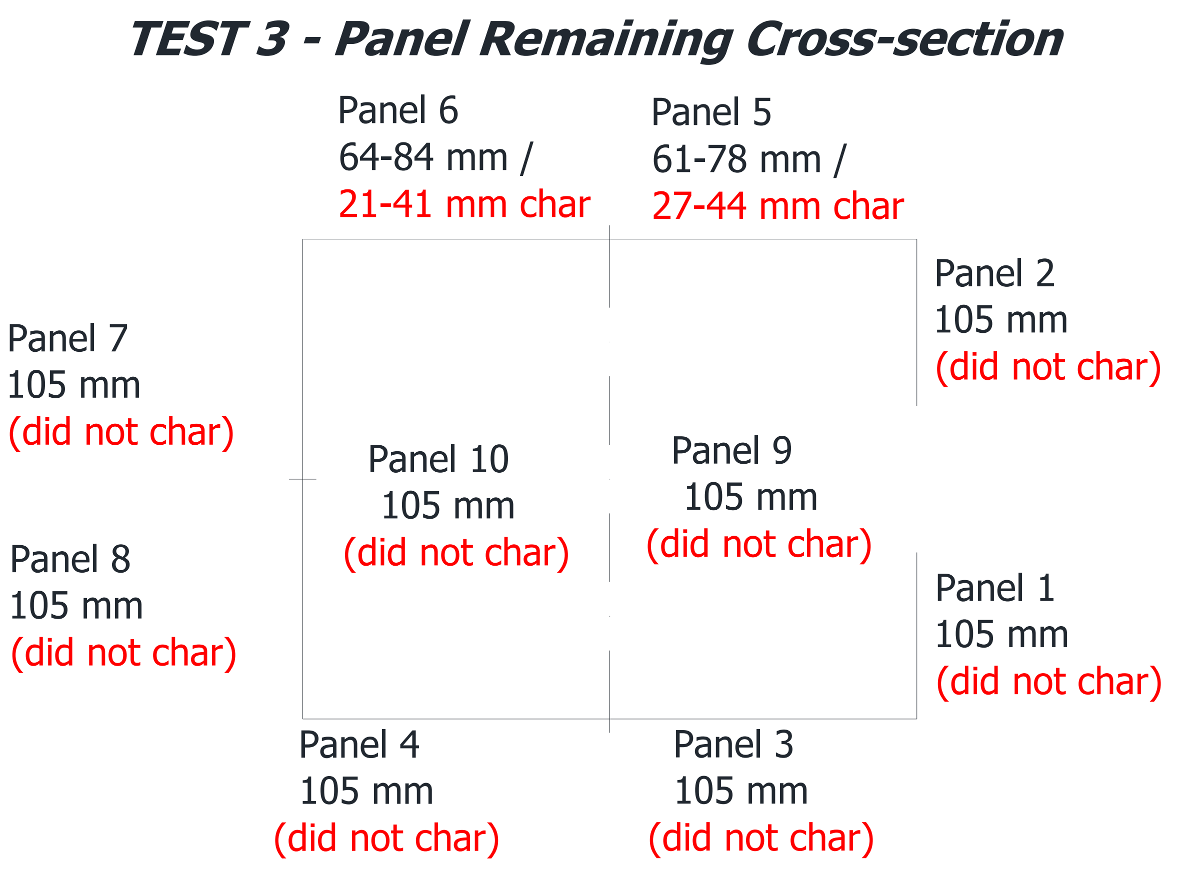

Figure 4-69: Plan view sketch of remaining cross-section thickness of CLT wall and ceiling panels after Test 3

4.3.6 Charring rate

The charring rate at multiple locations of the right side wall is presented in Figure 4-70.

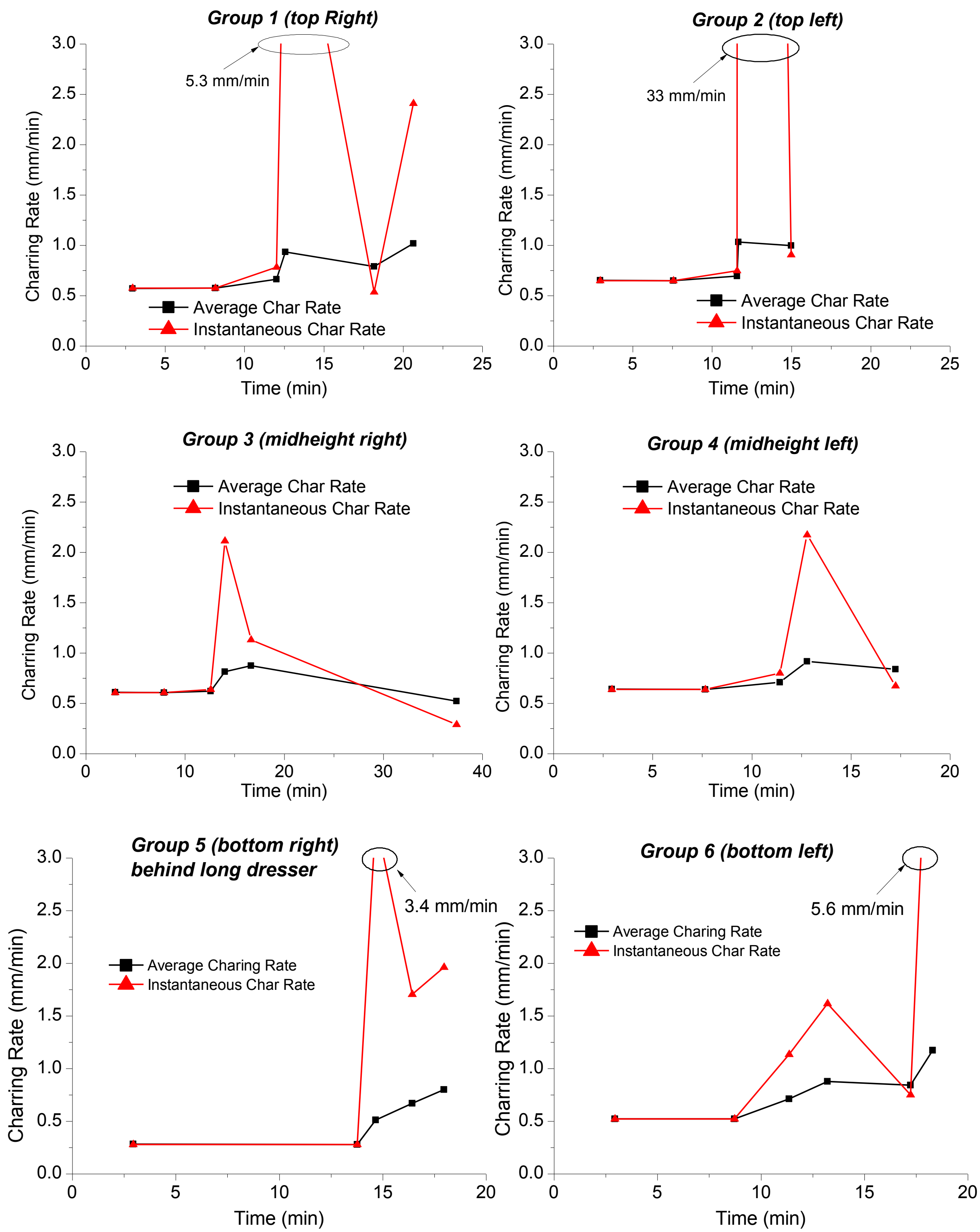

Figure 4-70: Charring rates at 6 locations in the unprotected right side wall during Test 3

The charring rates during this test were lower than in Test 1 and 2. The charring rates at the beginning of the test, while the content of the room is still burning, should be the very similar. Once the content of the room is consumed the CLT walls serve as the only fuel available. Test 3 had the smallest percentage of exposed CLT area which causes a lower average charring rate. Also, the room did not experience any delamination, allowing the char layer to serve as a thermal barrier for the unaffected wood which effectively slows down the charring rate. Table 4-5 provides a summary of the average charring rate of the six thermocouple wall groups located on the right side wall. Table 4-6 provides a summary of the instantaneous charring rate of the six thermocouple wall groups on the right side wall.

Table 4-5: Statistical analysis of the average charring rate of the right side wall - Test 3

Average Charring Rate	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Group 1	6	0.75778	0.18809	0.57	0.7254	1.01637
Group 2	5	0.80484	0.19296	0.64935	0.69525	1.03211
Group 3	6	0.67452	0.13672	0.52265	0.61562	0.87393
Group 4	5	0.74796	0.12404	0.63694	0.70922	0.91463
Group 5	5	0.50722	0.23227	0.27701	0.51195	0.79947
Group 6	6	0.77348	0.24745	0.51993	0.77646	1.17218

Table 4-6: Statistical analysis of the instantaneous charring rate of the right side wall - Test 3

Instantaneous Charring Rate	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Group 1	6	1.68974	1.89344	0.53686	0.67789	5.26316
Group 2	5	7.25731	14.57732	0.64935	0.74813	33.33333
Group 3	6	0.89738	0.65438	0.28973	0.6216	2.11416
Group 4	5	0.984	0.66856	0.63694	0.67219	2.17391
Group 5	5	1.51803	1.29844	0.27701	1.70455	3.37079
Group 6	6	1.68563	1.95153	0.51993	0.94066	5.57621

5 NUMERICAL 1-D HEAT TRANSFER COMPUTER MODEL

5.1 Introduction

An important part of this research study was the completion of a numerical model to calculate the fire resistance of CLT wall and floor assemblies. The numerical computer model was first developed by Marc Aguanno [**30**] using Microsoft Visual Basic Express 2010 to predict the moment resistance of CLT floor slabs. A new module was developed and added to the numerical model to provide the ability to calculate the performance of CLT wall panels experiencing vertical as well as out of plane loads during a fire.

The model is based on previous research conducted on properties of wood and gypsum boards at elevated temperatures. The 1-dimensional heat transfer model calculates temperature along the gypsum board and the CLT panel during the fire. Using the computed temperature profiles the program calculates the corresponding reduction strength factors at every point throughout the cross-section. The program outputs bending resistance, panel deflection, axial load resistance, charring rate, char depth and most importantly the assembly failure time.

At the start of the program, the user has the option to calculate the fire-resistance of a floor or a wall assembly, and then the number of CLT plies, their individual thickness, and orientation as well as the floor span or wall height can be chosen. The user then selects what type of wood and grade makes up each ply, whether or not gypsum board protection is present and the number of layers, and the loading conditions. To calculate the temperature at each time step the user can select between common standard fire curves such as ASTM E119, ISO 834 and CAN/ULC-S101. An option also exists for a non-standard fire in which case the user fills out a 30 points time-temperature table. In addition, the user has the option to select the melting temperature of the glue holding the CLT plies together. Failure of the glue will lead to ply delamination which has a great effect on charring rate and consequently the fire resistance of the assembly.

5.2 Heat Transfer Equation

In order to calculate the temperature profile across the gypsum board and the CLT panels, it is necessary to solve the general heat transfer equation for the finite number of discrete points. The following summary of equations represents the way the numerical model determines the temperature at every point on the CLT panels and Gypsum board. The equations and ideas have been modified or taken directly from Marc Aguanno in *Fire Resistance Test on Cross Laminated Timber Floor Panels* [**30**].

The problem to model is a one-dimensional unsteady heat conduction where the temperature at every point is dependent on time and the temperature of the fire. First we must discretize time Δt and space Δx. The temperature depends on two indices, spatial, i, and time, m as shown in Equation (1). Figure 5-1illustrates the nodal points, (1, 2. 3, etc) as well as the segment thickness, (Δx).

$$T_{i,m} = f(x_i, t_m) \tag{19}$$

Where,

$$T_{i,m} = temperature\ at\ point\ x_i\ and\ time\ t_m.$$

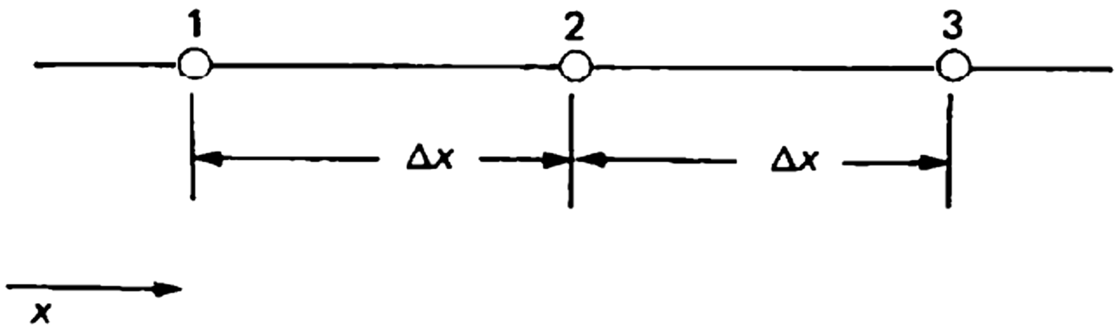

Figure 5-1: Node distribution and segment width [42]

The panel thickness, L, is divided into *N-1* equal segments from $i = 1$ for the surface exposed to the fire to $i = N$ for the unexposed surface. The number of nodes is specified by the user as an input. The width of the segments are defined as $\Delta x = L/(N-1)$. The rate of heat conduction into the control volume can be expressed as:

$$-k\frac{dT}{dx}\bigg| = -k\frac{T_{i,m} - T_{i-1,m}}{\Delta x} \quad for\ linear\ temperature\ gradient \tag{20}$$

Similarly the rate of heat conduction out of the control volume can be expressed as:

$$-k\frac{dT}{dx}\bigg| = -k\frac{T_{i+1,m} - T_{i,m}}{\Delta x} \quad for\ linear\ temperature\ gradient \tag{21}$$

The rate of energy stored in the panel is given by:

$$heat\ stored = \rho c \Delta x \frac{T_{i,m+1} - T_{i,m}}{\Delta t} \tag{22}$$

Adding all the energies together results in:

$$-k\frac{T_{i,m}-T_{i-1,m}}{\Delta x}+\dot{q}_G A\Delta x=-k\frac{T_{i+1,m}-T_{i,m}}{\Delta x}+\rho c\Delta x\frac{T_{i,m+1}-T_{i,m}}{\Delta t} \tag{23}$$

Where:

k	= thermal conductivity, W·m^{-1}·K^{-1}
A	= surface area through which heat is transferred, m^2
T	= Temperature, K
x	= node distance from surface, m
$\dot{q}_G$	= volumetric rate of heat generation, W·m^{-3}
ρ	= density of control volume, kg·m^{-3}
c	= specific heat capacity, J·kg^{-1}·K^{-1}
t	= time, s

Rearranging this equation and eliminating the second term on the left side of the equation since no heat is generated by the CLT or gypsum medium results in:

$$T_{i,m+1}=T_{i,m}+\frac{\Delta t}{\rho c\Delta x}\left[\frac{k}{\Delta x}\left(T_{i+1,m}-2T_{i,m}+T_{i-1,m}\right)\right] \tag{24}$$

We can simplify this expression by defining the Fourier number, F_o

$$Fo_i \stackrel{\text{def}}{=} \frac{k_i\Delta t}{\rho_i c_i\Delta x^2} \tag{25}$$

We can put the equation into its implicit form and substitute the Fourier number to solve nodes that fall within$(1 < i < N)$.

$$a_i T_{i,m+1} = b_i T_{i+1,m+1} + c_i T_{i-1,m+1} + d_i \tag{26}$$

Where:

$$a_i = 1 + 2Fo_i$$

$$b_i = Fo_i$$

$$c_i = Fo_i$$

$$d_i = T_{i,m}$$

The equation for the boundary conditions where $i = 1$ and $i = N$ changes slightly due to the segment's thickness as well as integration of convection and radiative heat transfers. For example the energy balance where $i = 1$ at the surface exposed to the fire is written as:

$$h_f\left(T_{f,m} - T_{1,m}\right) + \epsilon\sigma\left(T_{f,m}^4 - T_{1,m}^4\right) = -k\frac{T_{2,m} - T_{1,m}}{\Delta x} + \rho c\frac{\Delta x}{2}\frac{T_{1,m+1} - T_{1,m}}{\Delta t} \tag{27}$$

Where:

$$h_f = heat\ transfer\ coefficient$$

$$\epsilon = emissivity$$

$$\sigma = Stefan - Boltzmann\ constant$$

Substituting the Fourier number and solving for $T_{1,m+1}$ in its implicit form yields the following expression:

$$a_1 T_{1,m+1} = \mathrm{b}_1 T_{2,m+1} + c_1 + d_1 \tag{28}$$

Where:

$$a_1 = 1 + 2\text{Fo}\left[\frac{\Delta x}{k}\left(h_f + \epsilon\sigma\left[\frac{T_{f,m+1} + T_{1,m}}{2}\right]^3\right) + 1\right]$$

$$b_1 = 2\text{Fo}$$

$$c_1 = 0$$

$$d_1 = T_{1,m} + 2Fo\frac{\Delta x}{k}T_{f,m+1}\left(h_f + \epsilon\sigma T_{f,m+1}^3\right)$$

At the unexposed surface, where $i = N$, radiative heat can be ignored as temperature increase at this point is negligible. Convection heat transfer from the panel to the ambient air is introduced into the formulation to replace the non-existing conduction from node N to the air. The boundary condition at the unexposed is written as:

$$-k\frac{T_{N,m} - T_{N-1,m}}{\Delta x} = h_\infty\left(T_{N,m} - T_{\infty,m}\right) + \rho c\frac{\Delta x}{2}\frac{T_{N,m+1} - T_{N,m}}{\Delta t} \qquad (29)$$

And solving for $T_{N,m+1}$ in the implicit form gives:

$$a_N T_{N,m+1} = b_N + c_N T_{N-1,m+1} + d_N \qquad (30)$$

Where:

$$a_N = 1 + 2\text{Fo}\left[\frac{\Delta x}{k}h_\infty + 1\right]$$

$$b_N = 0$$

$$\text{c}_N = 2\text{Fo}$$

$$d_N = T_{N,m} + 2Fo\frac{\Delta x}{k}T_{\infty,m+1}h_\infty$$

$$T_\infty = ambient\ temperature$$

$$h_\infty = boundary\ surface\ convection\ coefficient$$

Initially, at $t = 0$, the temperature of all nodes in the CLT panel as well as in the gypsum is at ambient. By using the tridiagonal matrix algorithm (TDMA), the computer calculates the temperature of every node in the panel at each time step throughout the test. The temperatures calculated at a current time step are used to determine temperatures at a future time step. The matrix is formed using the previously defined implicit equations.

$$\begin{bmatrix} a_1 & -b_1 & & & & & \\ -c_2 & a_2 & -b_2 & & & & \\ & -c_3 & a_3 & -b_3 & \cdots & & \\ & & \vdots & \ddots & & & \\ & & & & -c_{N-1} & a_{N-1} & -b_{N-1} \\ & & & & & -c_N & a_N \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_{N-1} \\ T_N \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_{N-1} \\ d_N \end{bmatrix} \tag{31}$$

The blank spaces in the matrix represent zeros. By inverting the matrix, and knowing the coefficients of *a, b, c,* and *d* we can determine the temperature at every node.

$$AT = D \quad \rightarrow \quad T = A^{-1}D$$

5.3 Gypsum Board Protection

The option to use gypsum board allows the user to increase the fire resistance of the CLT wall or floor assembly. The gypsum board panels are divided into 40 nodes. At each time step, until gypsum board fails, the model determines the temperature at each of these nodes and assigns new properties such as density, specific heat capacity, and conductivity to them. When the temperature of a node in the gypsum board is between 100°C and 150°C, its specific heat capacity increases up to 18 times its original value [**43**]. A similar, yet less severe, process occurs in nodes of wood for temperatures between 100°C and 120°C. As the fire progresses and the chemically bound water in the gypsum is driven off, cracks start to form causing it to lose its originally tight connection with the screws connecting it to the CLT panel underneath.

The model accounts for the delay time due to driving the water out at which the temperature remains at around 100°C. Once all of the chemically bonded water is driven off, the temperature of the gypsum board starts to rise once again. The gypsum board does not contribute to the structural strength of these assemblies therefore its mechanical properties were not considered.

There have not been many studies or experimental data regarding the fallout time of gypsum attached to engineered heavy timber panels. To predict the gypsum falloff time in the model, it was decided to use the results obtained by FPInnovations during their full-scale CLT test [**44**]. The spacing between the screws connecting the gypsum board to the CLT panel has the potential to increase (shorter spacing) or decrease (further spacing) the fallout time. Filing the joints between adjacent layers of gypsum is also greatly important to ensure proper fire protection and avoiding premature gypsum failure. During the experiment, the screws were spaced every 12 inches in both the vertical and horizontal direction and the gaps properly sealed. The model does not account for differences in the applications and spacing of the screws and overall quality of construction.

5.4 Char Layer and Heating Zone

The numerical model assumes a point in the panel to become char once its temperature reaches 300°C. Any point in the panel that reaches this temperature is considered to have zero strength and therefore is eliminated from future model time steps. If the melting point of the adhesive selected by the user is less than 300°C, the ply is assumed to delaminate when the melting temperature of the glue is reached. The char depth then starts to build up once again starting at 0 mm of depth. The model does not incorporate char fall-off or regression, since information of this nature was unavailable in the literature. As the temperature at a node continues to increase pass the charring point, it provides less protection to the wood underneath. This is due to reduced density and heat capacity values and higher thermal conductivity. Once a node reaches 300°C and chars its mechanical properties diminish and do not contribute to the structural capacity of the member.

5.5 Failure Criteria

Of the three fire resistance failure criteria established by the CAN/ULC-S101-07 standard [**45**], the numerical code is able to check for two, structural and insulation criterion. The model does not include joints between plies and layers as they would require two- or three-dimensional analysis. Because of this, the model cannot determine if gases or flames are passing through and therefore cannot predict integrity failure.

The model deems structural failure if the assembly cannot support the load because of lack of moment resistance, compression resistance or excessive deflection. The model assumes insulation failure when the temperature on the last node (unexposed side) of the assembly exceeds ambient temperature by 140°C. The model evaluates the structural capacity of the assembly as well as the insulation criteria at each time step and determines whether it has reached failure. Once failure occurs, the model outputs the time and mode of failure, gypsum falloff time if applicable as well as the panel remaining thickness at time of failure.

5.6 Calculation Method

A flowchart of the model is shown in Figure 5-3. The numerical model performs the heat transfer and structural calculation in each time step until failure occurs. Figure 5-2 shows the graphical interface of the numerical model. The numerical model provides many alternatives for the user such as material properties and loading conditions.

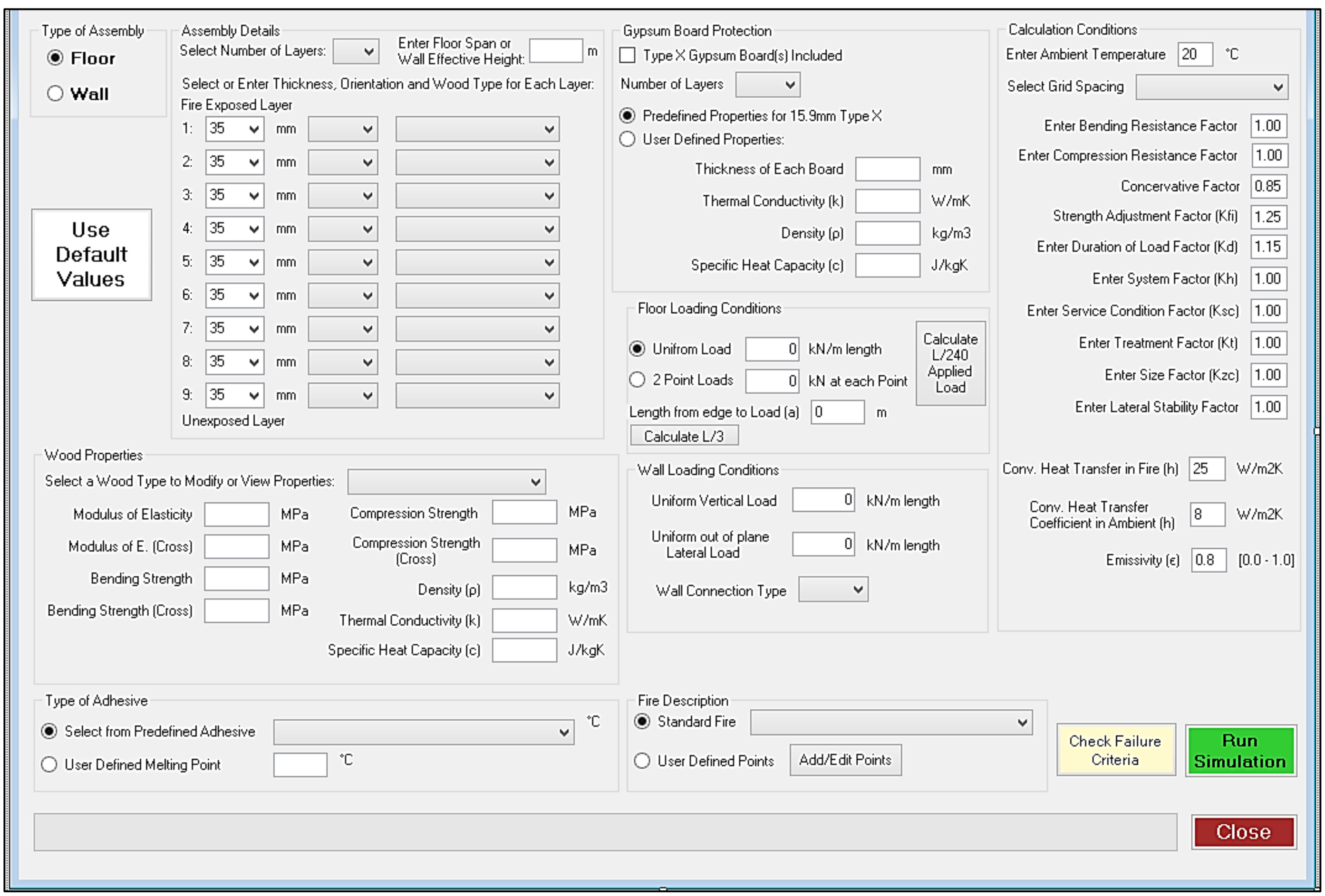

Figure 5-2: Graphical User Interface for Numerical Model to Calculate the Fire Resistance of CLT Floors and Wall Assemblies

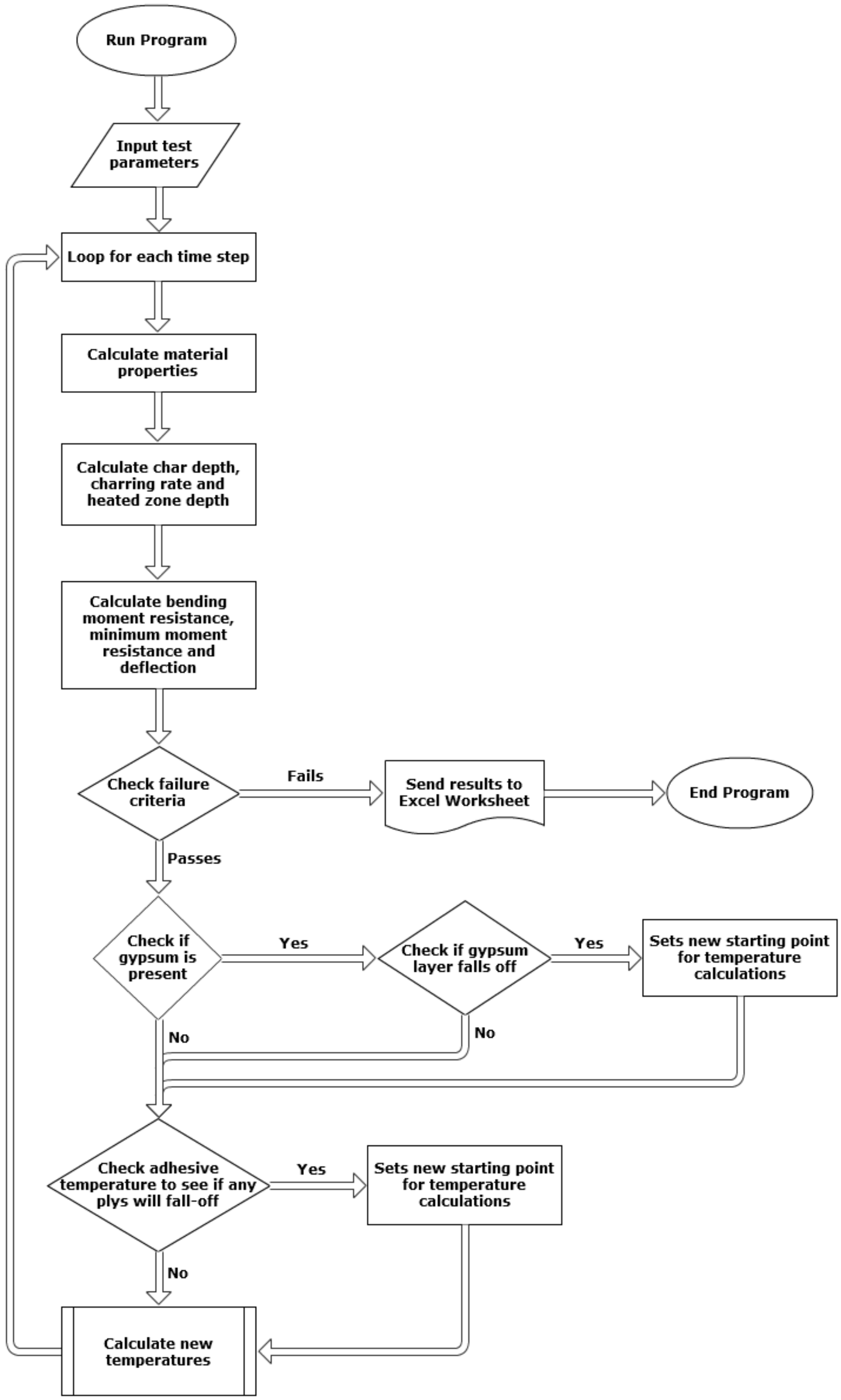

Figure 5-3: Process taken by the numerical model to calculate fire resistance of CLT [30]

5.6.1 Moment resistance of CLT floors

To calculate the moment resistance of the CLT floor assembly the Canadian Standard for Engineering Design of Wood (CSA O86) [**46**] was used. Although the shear capacity of the panels needs to be checked, moment capacity usually governs because of longer spans. As the panel heats up, the bending strength and other mechanical properties diminish until they reach zero strength at 300°C. Also the cross sectional area of the panels diminishes as it chars reducing the moment capacity of the panel. The orientation of the plies also plays a role in the calculation of the moment resistance. While the longitudinal plies carry the majority of the load, the model accounts for the minor contributions of transverse plies.

The CLT Handbook [**4**] recommends a slightly different method for calculating fire resistance than the one used by the model. The method consists in using only the cross section of the panel that is at ambient temperature for strength calculations. The CLT Handbook assumes a constant charring rate of 0.65 mm/min as well as a fix heat affected zone of 10.5 mm thick for fires longer than 20 minutes. Since the model calculates the temperature at each node at each time step, it provides more accurate results of charring rate and the overall affected cross section.

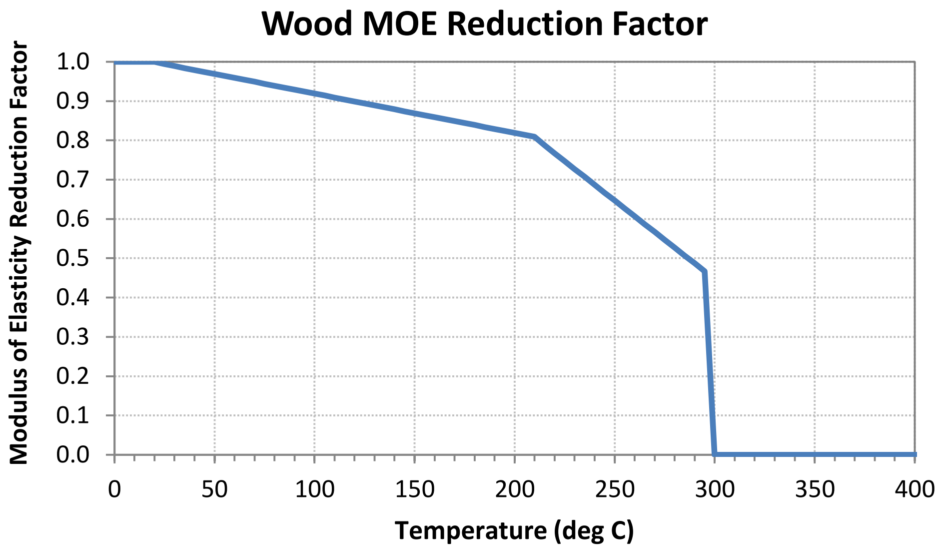

Figure 5-4: Reduction in wood modulus of elasticity multiplication factor used in numerical model [30]

The numerical model utilises a temperature-dependent relationship for the modulus of elasticity of wood, presented in Figure 5-4. This allows the model to accurately predict the strength at each node depending on its temperature. Once the neutral axis, effective stiffness and effective section modulus are determined by using the appropriate modulus of elasticity at each node, the moment resistance can be calculated as suggested by Wood Design Manual [**35**]and presented in Equation (32).

$$M_r = \phi F_b S_{eff} K_{zb} K_L \tag{32}$$

Where

$$\phi = reistance\ factor = 0.9$$

$$F_b = f_b(K_D K_H K_{Sb} K_T) \tag{33}$$

f_b = Specified bending strength of the wood (MPa), Sect. 5.3 CSA O86
K_D = Load duration factor, 1.15 (short-term duration for fire design)
K_H = System factor, 1

K_{Sb} = Service condition factor, 1 for dry conditions
K_T = Treatment factor, 1 for non-treated wood

S_{eff} = Effective section modulus (mm^3)

$$S_{eff} = \frac{EI_{eff}}{E(h_{fire} - \bar{y})} \tag{34}$$

$$EI_{eff} = \sum \frac{b_i h_i^{\,3}}{12} E_i + \sum b_i h_i d_i^{\,2} E_i \tag{35}$$

E = modulus of elasticity of ply with greatest tensile stress. Typically E from the outermost ply. E_1 (MPa)

$\bar{y}$ = distance from the unexposed surface of the panel to the neutral axis (mm)

h_{fire} = Effective cross-sectional depth remaining (mm)

K_{zb} = Size factor in bending

K_L = Lateral stability factor

These factors are all set to one by default but the user can change them if required. The section modulus is automatically recalculated as the temperature of the nodes and the distance between the neutral axis and the base of the char change with time.

The factor moment applied to the assembly depends on the loading conditions. Equation (36) displays the factored moment for an uniformly distributed load. The moment resistance in Equation (32) must be greater or equal to the factored load for the floor assembly to be adequate. Once the condition in Equation (36) is no longer met the simulation will end.

$$M_r \geq M_f = \frac{wL^2}{8} \tag{36}$$

Where

$w =$ Uniformly distributed load

$L =$ Span of the floor slab

5.6.2 Axial resistance of CLT wall

To calculate the axial resistance of the CLT wall panel, equations form the Canadian Standard for Engineering Design Wood (CSA O86) [**46**] were used. To calculate the axial resistance the following Equation (37) are used.

Slenderness Ratio

$$C_c = \frac{L_e}{\sqrt{\frac{12 \times I_{eff}}{A_{eff}}}} \tag{37}$$

Slenderness Factor

$$K_{c,fi} = \left[1 + \frac{F_{c,fi} \times K_{Zc} \times C_c{}^{3}}{35 \times E \times K_{SE} \times K_T}\right]^{-1} \tag{38}$$

Where:

$F_{c,fi} = f_c\ (K_{fi}K_DK_HK_{Sc}K_T)$

Where:

f_c = Specified strength of the wood in the strength axis (MPa)

K_{fi} = Strength adjustment factor

K_D = Load duration factor, 1.15 (short-term duration for fire design

C_C = Slenderness ratio

K_H = System factor

K_{Zc} = Size factor

E = modulus of elasticity of ply with greatest tensile stress.
Typically E from the outermost ply. E_1 (MPa)

K_{SE} = Service condition factor

K_T =Treatment factor

Compressive Resistance

$$P_{r,fi} = \emptyset F_{c,fi} A_{eff} K_{Zc} K_{c,fi} \geq P_f \tag{39}$$

Wall assemblies are subjected to second-order effects (i.e. P-Δ effects). The P-Δ effects refer to the added applied moment created by the initial axial load and added eccentricity as shown in Figure 5-5. The added eccentricity is due to a constant shift of the neutral axis as the wall chars only from one side. To calculate the fire-resistance of members under compression the procedures of Section 5.5.10 of CSA O86 for combined bending and axial loading are used.

$$\left(\frac{P_f}{P_{r,fi}}\right)^2 + \frac{M_f}{M_{r,fi}}\left[\frac{1}{1-\frac{P_f}{P_{E,fi}}}\right] \leq 1.0 \tag{40}$$

Where:

P_f = maximum induced axial compressive force in fire design

$P_{r,fi}$ = factored compressive resistance parallel to grain in fire design. Equation (39)

M_f = maximum induced factored moment in fire design

$$M_f = P_f \Delta \tag{41}$$

$M_{r,fi}$ = factored bending moment resistance in fire design. Equation (32)

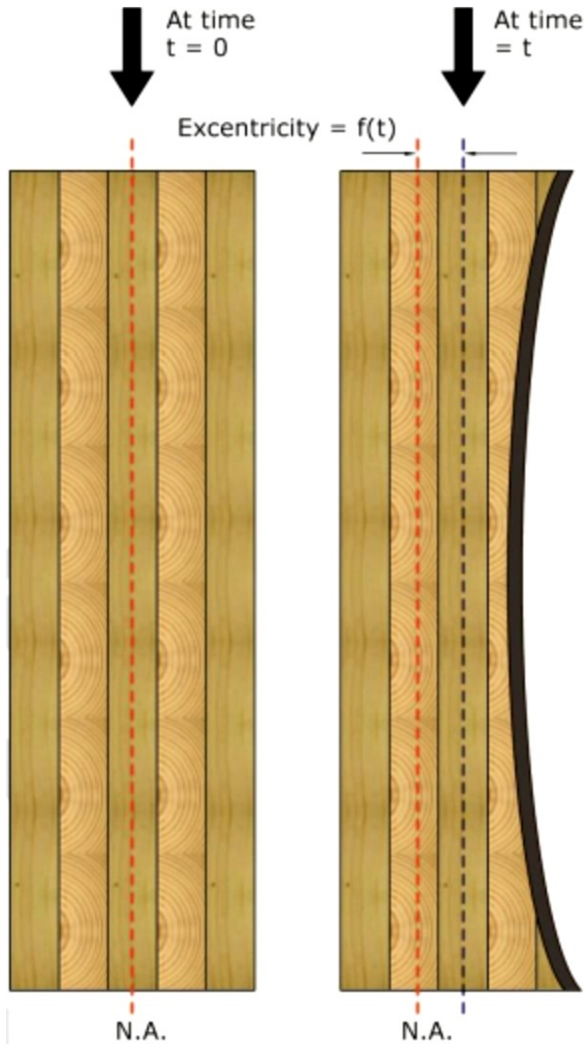

Figure 5-5: Eccentricity in a heavy timber wall due to fire [4]

Added eccentricity due to P-Δ effect:

$$\Delta = e + \Delta_f \tag{42}$$

$$e = \frac{h}{2} - \bar{y} \tag{43}$$

$$\Delta_f = \frac{(P_f e) L_e^{\ 2}}{16EI_{eff}} \tag{44}$$

$$P_{E,fi} = \frac{\pi^2 EI_{eff}}{L_e^{\ 2}} \tag{45}$$

Substituting the values into Equation (40) the numerical model determines if the assembly is adequate at each time step. Once the value of the equation is greater than 1.0 the model terminates and outputs the fire resistance of the wall assembly.

5.7 Numerical Model Results

The accuracy of the numerical model was evaluated by comparing its results with a series of CLT wall and floor tests conducted by Lindsay Osborne and Christian Dagenais of FPInnovations on July 2012 [**48**]. A total of eight full-scale CLT fire resistance tests were conducted at the National Research Council fire laboratory where the CLT panels were subjected to the standard ULC S101 fire exposure. The CLT plies were glued together using a polyurethane adhesive. Table 5-1 summarizes the characteristics of the eight tests conducted by FPInnovations.

Table 5-1: Summary of CLT floor and wall assembly tests conducted by FPInnovations

Assembly type	Gypsum board Protection	Applied Load	Other Test Characteristics
Test 1. 3 ply floor 4.786 m span and 0.763 m wide	2 layers of ½" type X	2.70 kN/m^2	38 x 89 mm boards. SPF 1650Fb-1.5E outer plies and SPF No.3/stud inner transverse ply.
Test 2. 3 ply wall 3.048 m in height and 0.763 m wide	2 layers of ½" type X	333.00 kN/m	38 x 89 mm boards. SPF 1650Fb-1.5E outer plies. SPF No.3/stud inner transverse ply.
Test 3. 5 ply floor with 35 mm ply 4.846 m span and 3.632 m wide	Unprotected	11.75 kN/m^2	35 x 89 mm boards. SPF 1950Fb outer and center ply. SPF No.3/stud inner transverse ply
Test 4. 5 ply walls with 35 mm ply. 3.048 m in height and 3.958 m wide	Unprotected	333.00 kN/m	35 x 89 mm boards. SPF 1950Fb outer and center ply. SPF No.3/stud inner transverse ply
Test 5. 3 ply floor with 35 mm ply 4.846 m span and 3.607 m wide	1 layer of $^5/_8$" type X	2.40 kN/m^2	35 x 127 mm boards. SPF No.1/No.2 visually graded lumber was used in all plies
Test 6. 5 ply floor with 35 mm ply 4.846 m span and 3.607 m wide	1 layer of $^5/_8$" type X	8.10 kN/m^2	35 x 127 mm boards. SPF No.1/No.2 visually graded lumber was used in all plies
Test 7. 7 ply floor with 35 mm ply 4.846 m span and 3.607 m wide	Unprotected	14.58 kN/m^2	35 x 127 mm boards. SPF No.1/No.2 visually graded lumber was used in all plies
Test 8. 5 ply wall with 21 mm ply 3.048 m in height and 3.660 m wide	Unprotected	72.00 kN/m	21 x 127 mm boards. SPF No.1/No.2 visually graded lumber was used in all plies

The fire resistance results of the eight tests conducted by FPInnovations along with the results obtained from the numerical model for each of these tests are presented in Table 5-2. The numerical model predicted that Test 1 did not fail after 8 hour of fire exposure while the physical test had to be terminated after 77 minutes due to equipment malfunctioning. The fire resistance of Test 3, 4, 7 and 8 were very similar between the physical test and the numerical model. In general the model seems to better estimate the fire resistance of assemblies with no gypsum board protection. The fire resistance of these assemblies is heavily depended on the ability of gypsum board to remain in place. The fall-off time of gypsum board can be difficult to estimate with high level of accuracy due variability in installation, position of fasteners and test fire characteristics. The fire resistance results of Test 5 and 6 are very different in the numerical model as compared to the full scale model. Both Test 5 and 6 were stopped early because of integrity failure. At this point the numerical model does not have the capabilities to predict integrity failure and therefore the fire resistance results are for structural failure.

Table 5-2: Fire resistance results of eight full scale tests conducted by FPInnovations alongside results from the numerical model.

Assembly type	Fire resistance of Physical Tests	Fire resistance of Numerical Model
Test 1.3 ply floor with 38 mm ply	77 minutes – no structural failure reached. Maximum deflection was 32.1 mm	No failure achieved after 8 hours of burning. 13.9 mm of deflection
Test 2. 3 ply wall with 38 mm ply	106 minutes. Structural failure. Maximum deflection was 47.5 mm	80 minutes. Failure due to buckling
Test 3. 5 ply floor with 35 mm ply	96 minutes. Integrity failure. Maximum deflection was 129.4 mm	94 minutes. Structural failure. Maximum deflection of 122 mm
Test 4. 5 ply wall with 35 mm	113 minutes. Structural failure. Maximum	102.9 minutes. Failure due

ply	deflection was 47.7 mm	to buckling
Test 5 – 3 ply floor with 35 mm ply	86 minutes. Integrity failure. Maximum deflection was 321.4 mm.	329.4 minutes or 5.49 hours. Structural failure. Maximum deflection of 124.5 mm
Test 6. 5 ply floor with 35 mm ply	124 minutes. Integrity failure. Maximum deflection was 153 mm	366.4 minutes or 6.11 hours. Structural failure. Maximum deflection of 122.9 mm.
Test 7. 7 ply floor with 35 mm ply	178 minutes. Structural failure. Maximum deflection of 170 mm	121.6 minutes. Structural failure. Maximum deflection of 71.1 mm
Test 8. 5 ply wall with 21 mm ply	57 minutes. Structural failure. Maximum deflection was 77 mm	51.2 minutes. Failure due to bucking

6 DISCUSSION

6.1 Test Setup

Table 6-1 provides a summary of the 6 tests that are relevant to the study of the performance of CLT rooms in fire. This includes the three tests with partial room protection conducted as part of this research study and three tests conducted by of McGregor [**3**]

Table 6-1: Room fire tests summary

	Partial Room Protection			**Fully Protected Walls & Ceiling**	**Fully Unprotected**
	Test 1	**Test 2**	**Test 3**	**McGregors' Room Test 2 & 4**	**McGregors' Room Test 5**
Unprotected CLT Area	20 m^2	22.5 m^2	11.25 m^2	-	53.61 m^2
Area of opening (door)	2 x 1.069 = 2.138 m^2				
Total interior surface area minus opening	69.36 m^2				
Protection Type	2 layers of ½ inch type X gypsum board, NO sprinklers				
Unprotected % of total interior surface area	28.8 %	32.4 %	16.2 %	0 %	100 %
Unprotected % area of the walls	52.8 %	59.4 %	29.7 %	0 %	100 %
Results	Self-sustain and re-ignition, early ply delamination. Manual extinguishment required		Self-extinguish no re-ignition, no ply delamination	Self-extinguished after furniture fire load was consumed	Major contribution of CLT to fire. Manual extinguishment required

The six tests used similar types and amounts of fuel consisting of bedroom furniture and clothes in addition to the hard wood floor. Furniture styles, manufacturer and furniture placement in the room were kept identical in all six tests. A single ventilation opening of about 2 m^2 was used in all tests. The tests differentiate mainly on the amount of wall surface area that was left exposed to the fire. Another important difference is that the ceiling was exposed only for one of the six tests, McGregor's fifth and fully unprotected test.

6.2 Charring Rate

An alternative approach to testing and numerical modeling for determining the fire resistance of a structural element is to use the expected time of exposure and the wood charring rate. As mentioned earlier, wood chars once it reaches a temperature of about 300˚C, after undergoing pyrolysis. To determine the charring rate of the CLT walls during the tests, embedded thermocouples were positioned at predefined depths in the walls. The time at which each point reaches 300˚C is recorded and used to determine the charring rate. At the beginning of the fire exposure the wood experiences a faster charring rate. Once the char layer increases in depth, it starts to perform as an insulation layer to the unexposed wood causing a slower charring rate. Typically in a standard fire resistance test, heavy timber chars at a constant rate of 0.65 mm/min once a char layer is present. Figure 6-1 compares the average charring rate of all three tests calculated by averaging the charring rate of all wall locations. A closer look shows a steeper slope early in the fire for Test 2 charring rate.

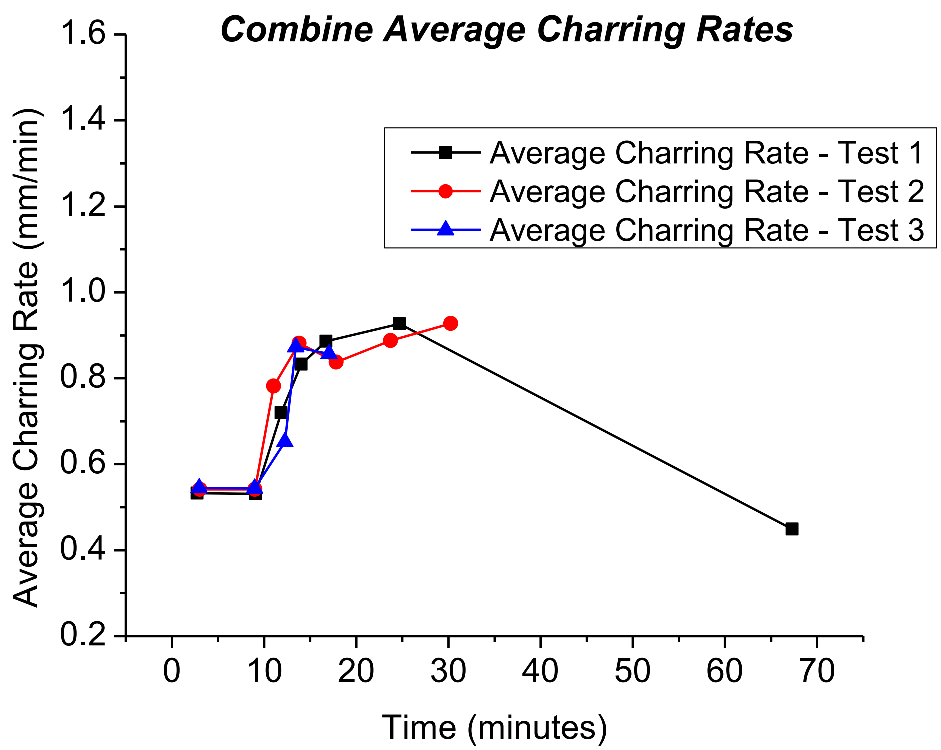

Figure 6-1: Combine average charring rate

The average charring rates of the CLT wall panels in Test 1, 2, and 3 were 0.69, 0.77, and 0.71 mm/min respectively. These charring rates are higher than the value of 0.65 mm/min prescribed by the CLT Handbook. The higher charring rates could be the result of the premature ply delamination which eliminates the protective char layer which serves as a thermal insulation and exposes fresh wood to the fire. Another reason for higher charring rates during the tests is that the temperatures early on in the room tests are far greater than in a standard fire test. The position of the two unprotected CLT walls in Test 2 facing each other was optimal for radiation between the two surfaces. This allowed the room and panels to remain hotter for a longer period of time and therefore having a greater charring rate.

6.3 Heat Release Rate

The room fire tests with full surface area protection conducted by McGregor provide a base measure of HRR and temperature to compare with other partially and fully unprotected rooms. These tests provide the fire characteristics of the room without the contribution of the CLT walls. Given that none of the walls or ceiling became involved in the combustion process throughout the duration of the test, the room can be deemed as of non-combustible construction. Figure 6-2, taken from McGregor's research shows a comparison between a fully protected Test 2 & 4 with fully unprotected Test 5. The fully protected test reached a maximum heat release rate of just over 5 MW while the fully unprotected room reached a HRR of about 7.2 MW.

Further examination of Figure 6-2 reveals a small discrepancy in the start times for the tests. Only 2 of the 3 lines on Figure 6-2 represent actual tests, the remaining line illustrates the difference in HRR from the unprotected room to the fully protected room. Since the maximum HRR of both tests did not occurred at the exact time, the resulting "CLT HRR Contribution" line series does not match up properly during the first 6 minutes of the test. The maximum difference in HRR between the tests presented is about 5 MW. This is a result of the slight delay in time of "Average HRR Test 2 & 4" series. The early CLT contribution of 5 MW represented by the curve is therefore nonexistent. Once the furniture has been consumed, the main contribution to the Heat Release Rate in the room is the CLT panels. The maximum HRR contribution from CLT occurs towards the end of the test when the CLT panels are the only remaining fuel available.

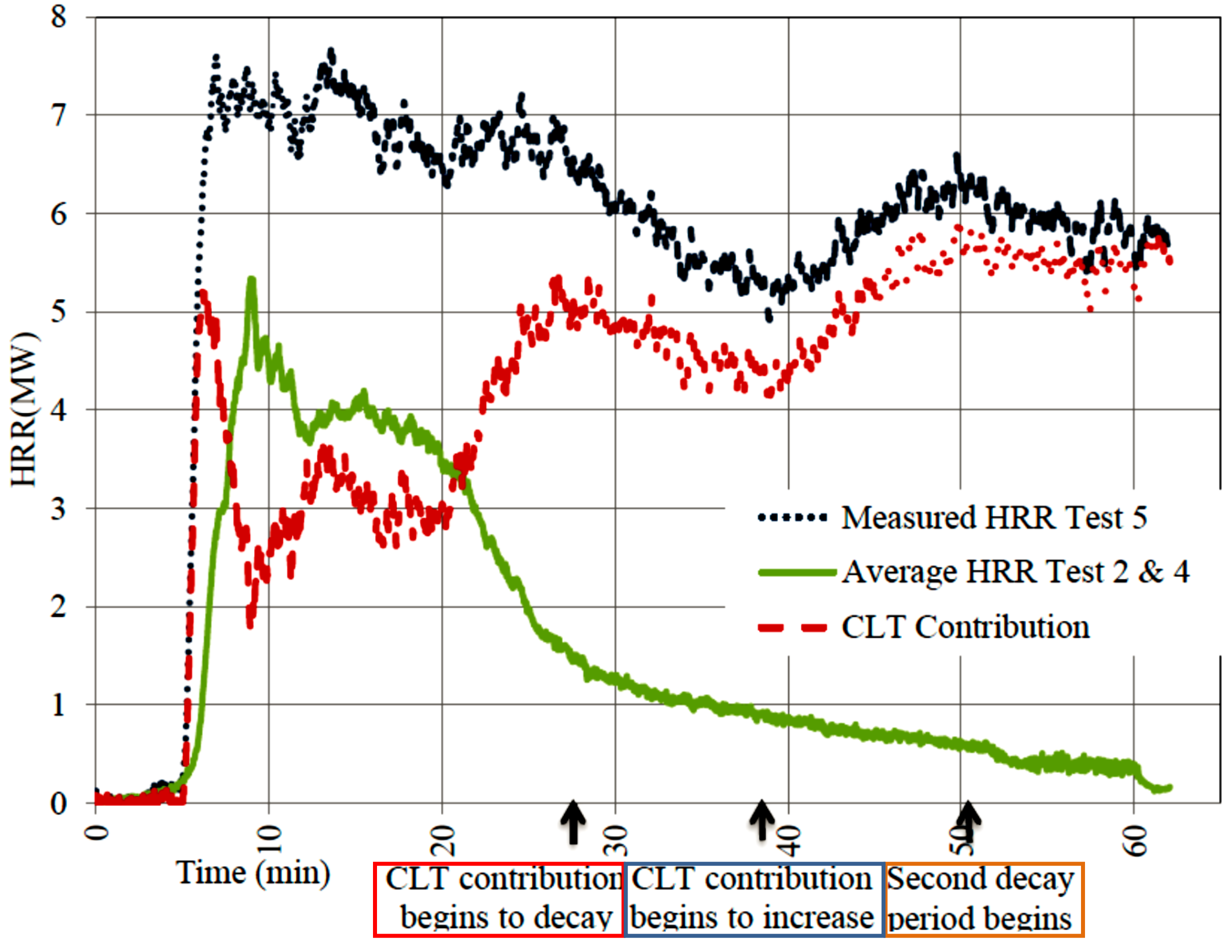

Figure 6-2: Heat release rate contribution of CLT and furniture from McGregor's room tests [3]

The test results from fully protected rooms and fully unprotected rooms yield the following conclusions. In rooms 2 & 4 with protected walls, the CLT panels never became involved in the burning process and the fire ultimately self-extinguished after the furniture in the room had been consumed. Test 5 in which all room interior surfaces were left exposed continued to burn vigorously after the furniture was consumed producing large exiting flames out of the single opening. This test was characterized by the heavy involvement of the CLT panels after the initial room flashover. The results depicted in Figure 6-2 represents the two most extreme scenarios for protection options but it does not answer the fundamental question of whether or not CLT can be safely used in family dwelling units.

To provide a comparison of the rom fire characteristics and the contribution of CLT walls to the fire, the results of the fully protected and fully unprotected room tests are shown together with the results from the three partially protected room tests conducted in this work in Figure 6-3.

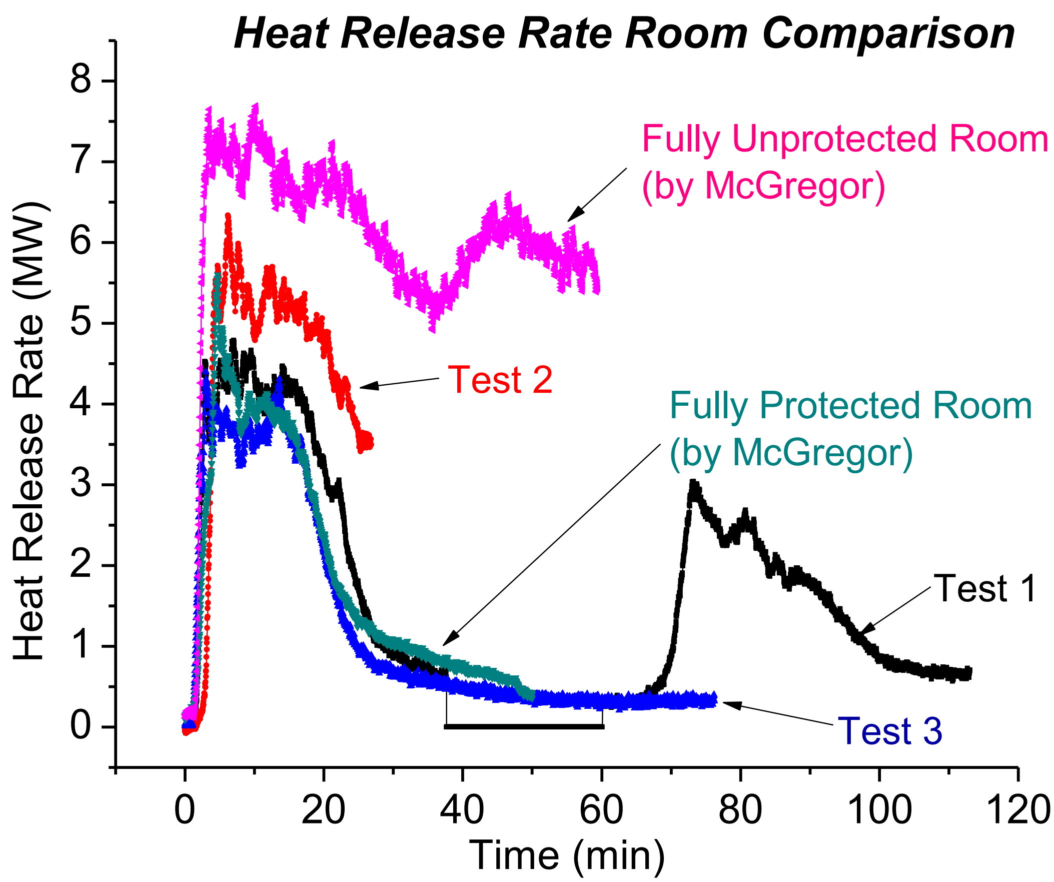

Figure 6-3: HRR of the 3 partially protected rooms as well as McGregor's fully protected and fully unprotected room test

The highest HRR output shown in Figure 6-3 is for the room with unprotected CLT panels. The second partially protected room test with a total unprotected surface area of 22.5 m^2 or 59.4 % of the total wall surface area produced the second highest HRR output of 6.33 MW. Partially protected room test one with a total unprotected surface area of 20 m^2 or 52.8 % of the total wall surface area had a maximum HRR of 4.79 MW. The third and final partially protected room test which had only one wall unprotected totalling 11.25 m^2 or 29.7 % of the total wall surface area had very similar HRR output from what was obtained by McGregor's completely protected room. Table 6-2 summarizes the maximum and average HRR for the three partially protected rooms conducted during this research and the fully protected and unprotected room tests conducted by McGregor [**3**]. The average HRR was taken over the first 26 minutes of each test as this was the longest time in which HRR data was available in all five tests. The average was also taken to eliminate spikes in data that could result in poor test assessment.

Table 6-2: Comparison of HRR results between five CLT room tests

	Maximum HRR reached (MW)	Total heat produced through first 26 minutes of test (MJ)
Room Test 1	4.79	5275
Room Test 2	6.33	6702
Room Test 3	4.40	4383
Fully Protected Room Test by McGregor	5.60	4581
Fully Unprotected Room Test by McGregor	7.69	9864

The average HRR in Test 3, with only one wall unprotected, and the fully protected room show similar results. Figure 6-3 shows that both tests have similar HRR behaviour characterised by a rapid increase early in the tests followed by a constant decrease once the room contents were consumed. The comparable energy outputs between the tests suggests that the main fuel that contributed to the fire was the furniture and that the unprotected CLT wall was not a major contributor especially following flashover. Additionally, Test 1 with the adjacent unprotected walls had similar characteristics as Test 3 and to the fully protected room test. The only difference was the second flashover at the 70th minute in the test due to premature delamination. This demonstrates that in terms of energy output, the number of unprotected walls (up to 2 walls) does not play a significant role in the total Heat Release Rate of a room of similar dimensions with a single opening.

The third room test was the only one which did not exhibit any CLT ply delamination. The char layer was able to remain in place during the entire test which slowed down the charring rate of the room. The char layer protected the underneath unburned wood effectively decreasing the availability of fuel which contributed to a decrease in HRR. The single unprotected CLT wall limited the contribution of CLT to the fire early in the test. The HRR and temperature output were not as high as in the first two tests which could have contributed to a slower charring rate allowing the first CLT ply to remain in place throughout the test.

6.4 Room Temperature

The three room tests exhibited similar temperature behaviours with slight variations. At the beginning of each test, the bed was the first ignited item and together with the rest of the furniture was the main fuel during the first stages of the fire. Figure 6-4 illustrates the interior room temperature for the three room tests measured by the plate thermometer as well as the temperature profile of the protected and unprotected room tests conducted by McGregor. The room temperatures had a sudden increase due to flashover and then incrementally increase until they reach their maximum temperature. In each tests, the maximum flashover temperature is about 200 °C less than the maximum value. Test 1 and 2 reached a maximum temperature of about 1200 °C while Test 3 with only one wall unprotected reached a maximum temperature of

800 °C. There is no significant difference in terms of maximum temperature between the fully unprotected room and the partially protected room. The only difference occurs 25 minutes into the test. While the temperature in the partially protected rooms starts to decrease at this point, the fully unprotected room experiences slightly increasing temperatures.

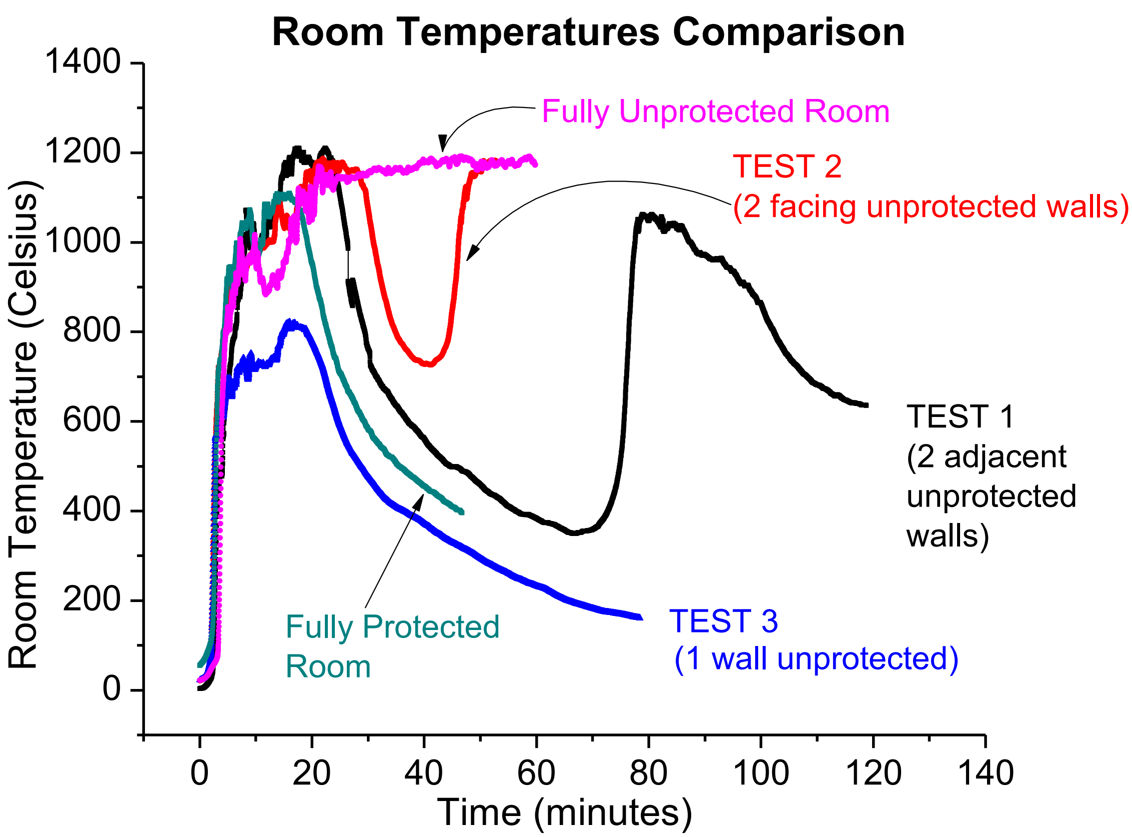

Figure 6-4: Temperature comparison of partially protected, fully protected and fully unprotected room tests

The only physical difference between the 3 rooms is the number of unprotected walls and consequently the total amount of unprotected wall area. The maximum temperature in Test 1 and 2 is similar to the maximum temperature of the fully protected and fully unprotected room tests. This suggests that the number of exposed walls does not have a significant impact on the maximum temperature in the room in the early stages of the fire. This is mainly because the furniture acts as the main fuel burning during the early stages of the test with minimal contribution from the CLT panels. The data shown in Figure 6-4 was measured by a plate thermometer to account for radiation heat transfer from the flames and room surfaces.

The three rooms reached a maximum temperature within 25 minutes from ignition. The temperature in the room started to decrease after 25 minutes as most of the furniture and clothing were consumed. In addition, the unprotected CLT walls developed a char layer which limited the burning of the unprotected wood underneath. As combustion started to decrease, the HRR and room temperature decreased.

Unlike the rest of the tests the maximum temperature recorded by the plate thermometer during Test 3 was only 800°C, which is much lower than the 1200°C recorded by the other four room tests. Figure 6-5 shows the detailed temperature across the entire room by graphing the average temperature of each of the four thermocouple trees as well as the plate thermometer. Thermocouples Trees 1 and 2 which were located at each side of the bed towards the back corners of the room recorded a maximum average temperature of 1100 °C, while thermocouple Trees 3 and 4 as well as the plate thermometer located near the room opening recorded a maximum temperature of about 800 °C. This difference in temperature between the thermocouple trees was not seen in Test 1 and 2. Figure 4-10 and Figure 4-34 show the temperature recorded by each thermocouple Tree in Test 1 and 2 respectively. It is uncertain what might have cause the discrepancy in temperature in Test 3.

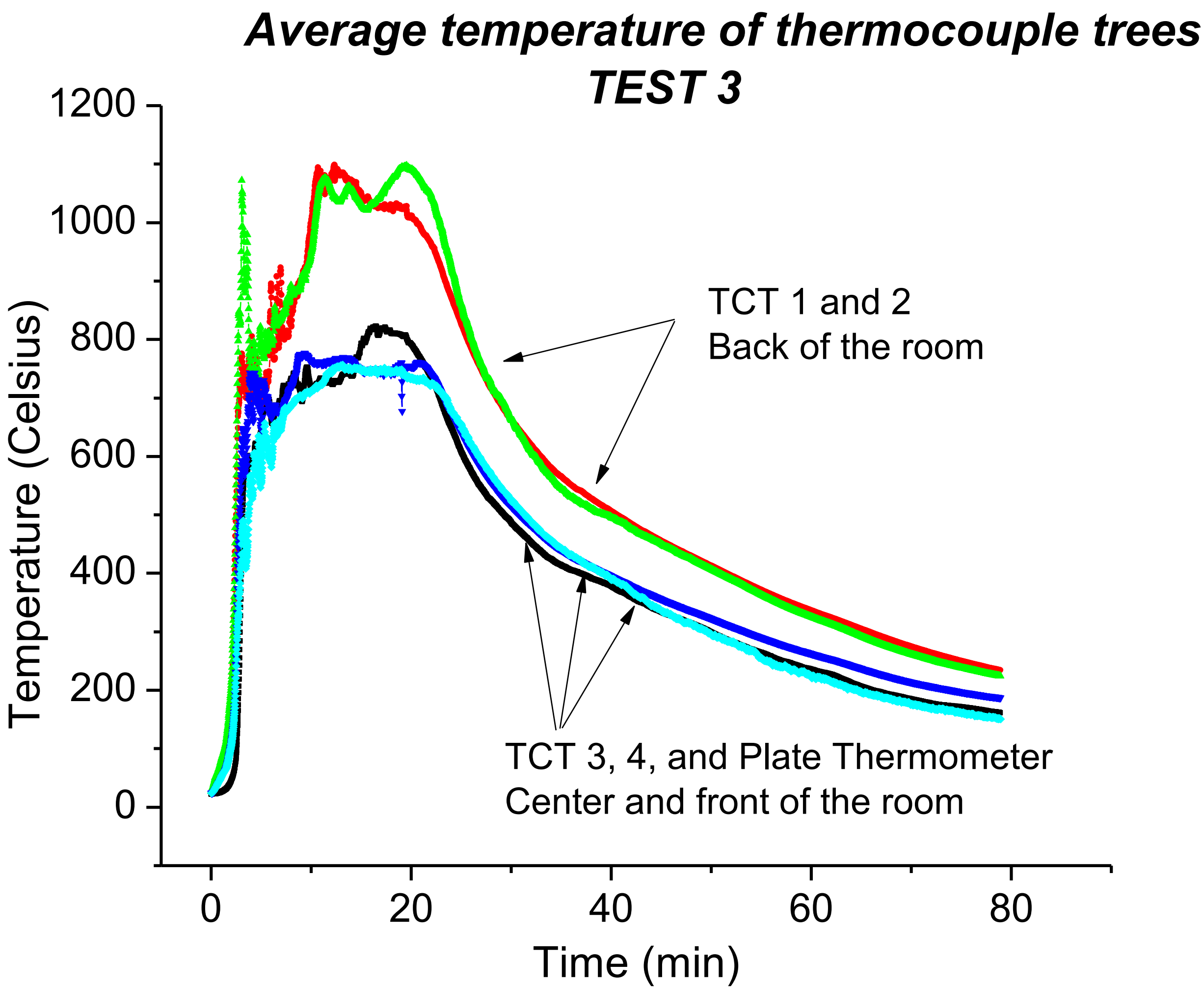

Figure 6-5: Detailed interior room temperature of Test 3

6.5 National Building Code Restrictions on Tall wood Buildings

The National Building Code of Canada (NBCC) Division B Part 3 permits combustible, as well as non-combustible construction of buildings. Non-combustible construction refers to the use of concrete and steel as the main structural components. Combustible construction mainly refers to the use of wood as the primary structural material. There are two types of wood construction, light wood framing, and heavy timber framing which includes CLT.

The NBCC currently limits the use of buildings constructed out of combustible materials to a maximum of 4 storeys 3.2.2.45 (1). Also as per 3.2.2.45 (6), the NBCC limits the maximum physical height of a combustible building to 18 meters. Table 3.2.2.50 of the NBCC limits the building area depending on the number of storey and the number of streets the building faces. Table 6-3 shown below is adapted from the NBCC for a building with a 1 hour fire resistance rating for floors, mezzanines and loadbearing vertical assemblies [**2**].

Table 6-3: Building size relative to number of storeys for buildings with 1 hour fire resistance rating

No. of Storey	Maximum Area, m^2		
	Facing 1 Street	Facing 2 Streets	Facing 3 Streets
1	Not limited	Not limited	Not limited
2	7200	Not limited	Not limited
3	4800	6000	7200
4	3600	5000	5400

These restrictions on combustible buildings were set to minimize occupant and firefighters' life risk as well as to reduce property damage and overall losses. The main concerns of the code committees were fire spread, fire intensity, fire separation and fire resistance rating of building's structural elements. Table 6-4 summarizes the fire resistance and sprinkler requirements of a Group D building based on its number of storeys and construction type.

Table 6-4: Requirements of Group D Occupancy Buildings. [49]

Category	**Maximum Building Height**	**Construction Type**	**Floor and Support Fire Resistance Rating**	**Sprinkler Protection**
Low-Rise	3 Storeys	Combustible	45 minutes	Yes and No
Low-Rise	4 Storeys	Combustible	60 minutes	Yes
Mid-Rise	6 Storeys	Non-combustible	60 minutes	Yes and No
High-Rise	Unlimited	Non-combustible	120 minutes	Yes

6.5.1 Structural capacity of CLT panels

The numerical heat transfer model presented has the ability to calculate the fire resistance of loaded CLT wall and floor assemblies. Model outputs show that 3-ply and 5-ply CLT floor and wall panels are adequate to withstand the prescribed loads. The model results are confirmed by the lab tests completed by Marc Aguanno [**30**] who performed a series of 3-ply and 5-ply CLT floor tests using 1 or 2 layers of gypsum protection under standard and non-standard fires. The numerical model provided fire resistance results for wall and floor assemblies that were similar to those obtain by test conducted by FPInnovations as highlighted in Section 5.7 of this thesis.

The room fire tests conducted during this study did not examine the structural capacity of the CLT wall panels. The experiments did monitor the temperature behaviour at the panels' cross section showing that after 2 hours of fire exposure the unexposed side of the wall remained at room temperature. The fire was contained in the room throughout the test without the escape of flames or gases though the panels or panel joints.

6.5.2 Fire separation characteristics

The CLT panels tested showed no signs of flame spread outside the confined boundaries of the room with exception of the door which served as the only room opening. Figure 6-6 shows the temperature profile of the unprotected CLT wall during Test 1. The furthest thermocouple located 24 mm from the interior surface shows that the wood at that location did not char until after 80 minutes into the test which demonstrates the fire resistance capacity of these solid wood panels. The high temperatures (>300 °C) recorded by the thermocouple in Figure 6-6 are not indicative of the panel temperatures but the room temperature as the thermocouples become directly exposed to the fire as the char burned away.

An important behaviour is displayed in Figure 6-6 as the wood starts to heat up. The temperature plateaus as it reaches 100°C. As the moisture in the panel evaporates, the temperature at that point in the panel remains around 100°C. Thermocouples embedded closer to the fire exhibit a shorter plateau time while thermocouples embedded deeper in the panel remain at 100 °C for longer periods of time. This is due to the added moisture from the wood initially involved in pyrolysis which is driven into the unaffected wood cross-section, effectively delaying the burning of the panels and increasing their fire resistance.

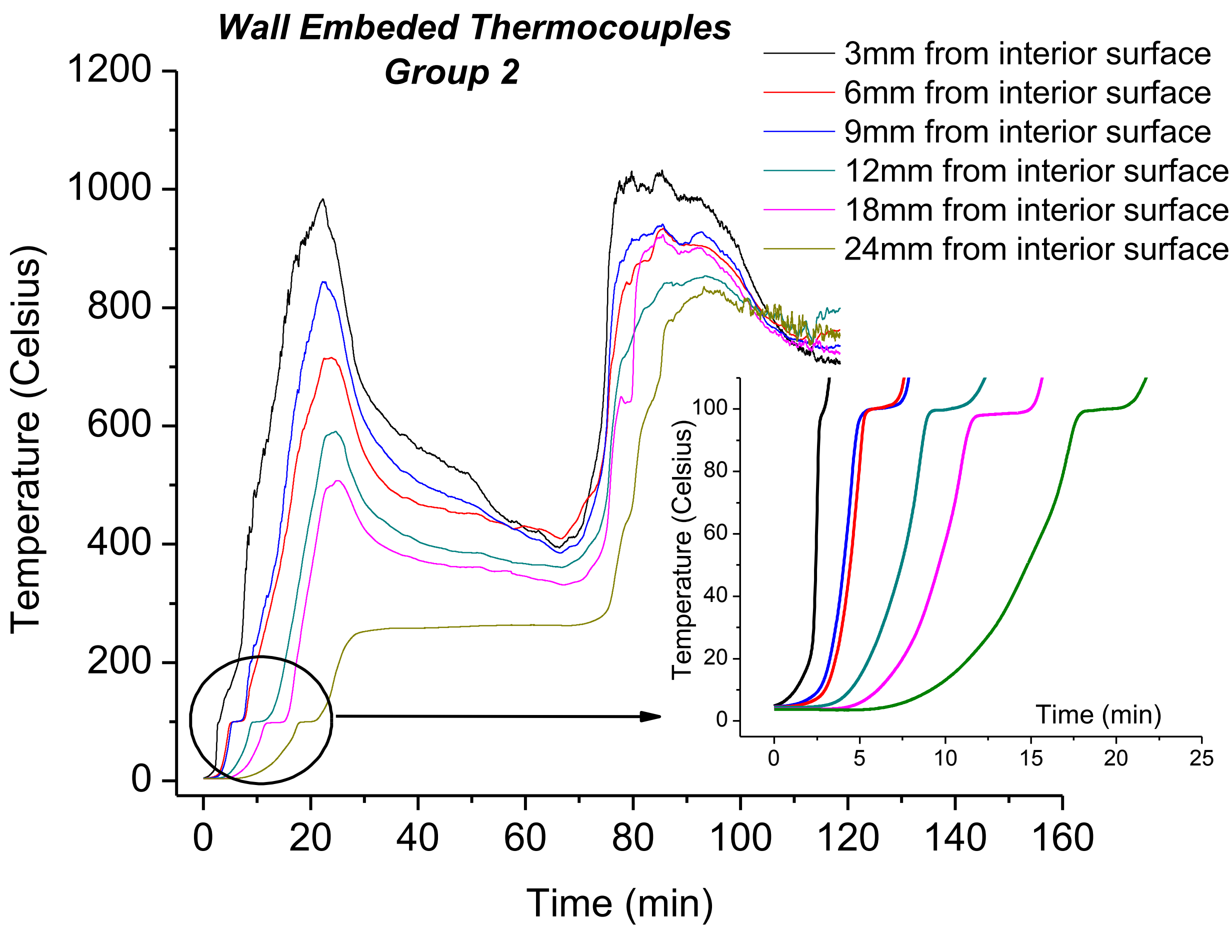

Figure 6-6: Cross section temperature of unprotected CLT wall panel in Test 1

6.5.3 Compartment fire

A major concern with the use of combustible construction in a compartment is the notion of added fire spread risk and the increased involvement of the room lining in the fire. In terms of heavy timber framing as in the case of the tested CLT rooms, results show no major involvement of the CLT panels during the first 45 minutes of the fire for rooms with two walls and one wall unprotected. Furthermore, the room test with one wall unprotected resulted in fire self-extinguishment after the room contents were consumed. The unprotected walls in the partially protected room tests did not have a major contribution to the fire except when premature delamination of the first layer took place.

During a building design, compartment fires get the most consideration. If the fire remains within the fire compartment, the risk of fire spread to other parts of the building is minimized, therefore limiting property damages and fatalities. In the early stages of the fire (Growth Stage), the Building Code focuses on limiting the spread and growth of fire, to facilitate occupant evacuation and limiting property damages. To limit the growth stage of the fire and allow the fire protection strategy such as sprinklers, smoke detectors, fire separations to perform as designed, the Building Code limits floor building area and the number of stories depending of type of occupancy. The full scale partially protected room fire tests showed that the heat release rate before flash over was similar to the fully protected room which in comparison behaves as a non-combustible building.

Once the compartment has reached flashover, the objective of the NBCC is to limit fire spread outside the compartment and limit partial failure or collapse of the building. Focus on life safety shifts to occupants evacuating outside the burning compartment. At this stage, the fire separation and insulating capacity of the walls, floor and ceiling are critical in preventing fire spread outside the compartment. The room fire tests showed that during the duration of the tests, no walls (including the unprotected walls) allowed flames or gases to escape except when proper fire rated caulking was not used to seal the wall panel lap joints. In terms of thermal insulation, the unaffected side of the walls remained at room temperature throughout the duration of the tests. Structurally, the CLT walls and floor panels tested by FPInnovations [**44**] under CAN/ULC S101 standard fire test and Aguanno [**30**] using both standard and parametric fires failed well after 60 minutes of exposure. The 1-dimensional heat transfer model reaffirmed that the CLT panels are structurally adequate to withstand a 1 hour fire without added protection and reached close to 2 hour fire resistance when 2 layers of ½" gypsum board protection was used.

6.5.4 Fire detection systems and sprinklers requirements

The National Building Code of Canada requires combustible buildings higher than 3 storeys to have sprinklers, while a 6 storey non-combustible building may not be required to do so. The fire characteristics of the partially protected CLT rooms were very similar to the fully protected CLT room fires which performed similarly to a non-combustible room fire. A redesign of the sprinklers requirement is not recommended to partially protected CLT rooms. In terms of fully unprotected CLT rooms, considerations might be given to faster response, more effective sprinklers given the added contribution of the walls. The same sprinkler design should be used in the entire building.

Section 3.2.4.1 of the NBCC states the building requirements for fire detectors. The test results of this research study do not suggest altering the recommendations for fire detectors. The fire intensity, growth rate and duration were comparable between partially protected rooms with one wall unprotected and the fully protected room.

7 CONCLUSIONS

The main objectives of this research included:

1. Construct and study the behavior of partially protected CLT wall panels in a non-standard room fire.
2. Study how the heat release rate, temperature, fire duration, and charring rate differ as the area of unprotected CLT surfaces in the room increases.
3. Identify the maximum CLT surface area that could be left unprotected and still yield self-extinguishment after complete room content burn out similarly to a fully protected room.
4. Study the process of CLT ply delamination and its effects on a room fire.
5. Study the falloff time of the gypsum board protecting walls and ceiling surfaces.
6. Addition of code to the already existing numerical heat transfer model developed by Marc Aguanno [**30**] in order to calculate the fire resistance of loaded CLT wall panels exposed to a fire.

Many of these objectives were addressed after observations made during the three partially protected room fire tests and analysing the data output afterwards. The following conclusions were drawn from these tests.

1. All three room test had the same dimensions, ventilation opening factor, room content and were subjected to a non-standard fire.
2. The heat release rate during the tests with two walls exposed was much greater than the heat release rate of the test with only one wall exposed.

3. The maximum HRR of Test 2 with unprotected walls facing each other was greater (6.3 MW) than the HRR of Test 1 (4.8 MW) in which the unprotected walls were adjacent to each other. Perhaps the greater radiation between walls in Test 2 due to a higher configuration or view factor led to higher burning rates.
4. Room temperatures during the early stages of the fire for all three tests were similar as only the room contents were involved in the fire. After flashover, the temperatures in the rooms with multiple unprotected walls decreased at a slower rate than the room with only one unprotected wall.
5. After an early integrity failure during Test 2, it was concluded that the use of fire rated caulking to seal lap joints connecting walls as well as any other CLT panel to panel connection is necessary. The lack of use of a sealant will allow hot gases to escape the fire room which could lead to flaming outside the room.
6. Premature delamination of CLT plies occurred in the first two tests with 2 walls unprotected. The first exposed CLT ply did not char fully before the adhesive failed, exposing the underneath ply and adding new fuel to the fire. Delamination of the plies was the reason for the second flashover during Test 1 and 2. Test 3 with only one wall exposed did not delaminate.
7. The CLT panels used for the construction of the third room were produced by a different manufacturer than the one which produced the CLT for Test 1 and 2. These panels had wider plies with more adhesive per ply which may have contributed to full ply charring without delamination.

8. The charring rate of the unprotected walls was higher for Test 1 and 2 where the heat release rate was greater. The charring rate decreased linearly in all three tests as the thickness of the char layer developed.
9. Test 3 self-extinguished after all the contents in the room had been consumed with no major involvement of the CLT unprotected wall in the fire. The heat release rate and temperature in Test 1 decreased rapidly after the room contents were consumed but the fire re-ignited causing a second flashover due to burning of the second layer because of premature ply delamination. Tests 1 and 2 were manually put out by firefighters after the fire did not self-extinguish.
10. Test 3, with only the right wall unprotected, self-extinguish and performed similarly to the fully protected room test conducted by McGregor.
11. The results of the developed numerical model show that the model can accurately predict the structural failure of CLT walls when subjected to the standard time-temperature test.

Overall the partially protected CLT room tests demonstrated that a certain percentage of the room interior surface area can be left unprotected without increasing the risk of fire spread or increased fire intensity. The study demonstrated that for a 4.5 x 3.5 x 2.5 m room with a door opening of 2.0 x 1.0 m with one wall unprotected accounting for 29.7 % of total room wall area performed similarly to a fully protected room and resulted in self-extinguishment after the room contents were consumed.

Given the results from the room tests, the construction limitations on Cross Laminated Timber should be addressed. The walls and ceiling exceeded the required fire resistance rating of 1 hour for a building of a maximum of 6 storeys. Provided the walls and ceiling are properly sealed and protected with gypsum boards, CLT panels can be used in the construction of much taller buildings. The use of sprinklers is recommended as it ensures that fires will be suppressed with no fire department intervention. The premature delamination of plies is could be problematic but this should not be a concern if sprinklers are installed.

8 FUTURE RESEARCH

This research investigates the fire behaviour of partially protected rooms when exposed to a non-standard fire. The tests concluded that rooms containing two unprotected walls resulted in continuous burning due to premature delamination while a room with only one unprotected wall behaved similarly to a fully protected room. There are a number of variables that can be further explored to provide a more complete picture regarding the protection of CLT walls. For example, in future research it would be beneficial to understand the effects of adhesives with melting points higher than 300°C. Having this type of adhesive would eliminate the delamination issue which could potentially prolong the fire resistance of the CLT.

The use of CLT panels with wider plies could also be explored. During the third room test, panels with wider plies were used which could have contributed to an increase resistance to delamination which occurred during the first two room tests. Having thicker plies could also improve the fire resistance of the panels by reducing the probabilities of ply delamination. The char front would take longer to reach the adhesive line, completely reducing or prolonging the possibility of delamination.

More research could be conducted to study the behaviour of unprotected CLT ceilings, both with and without the use of sprinklers. The ceiling represents a large portion of the interior area of the room (15.75 m^2). This unprotected area falls between Test 1 with two unprotected walls (20 m^2) which delaminated, and Test 3 (11.25 m^2) which did not.

Future tests could look at having a greater ventilation factor by adding a second opening such as a window. All three tests conducted exhibited large exiting flames along the top of the door opening. This combustion taking place outside the room together with the large amounts of soot and smoke produced indicates that the fire was oxygen deprived or controlled by ventilation. Having a larger ventilation factor could provide a more severe non-standard fire.

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