External Research Report ER68 [2021]

Passive Fire Protection of Cross Laminated Timber

Project QR01810

OFR Consultants, funded by the Building Research Levy

Funded from the Building Research Levy

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ISSN: 2423-0839

Passive Fire Protection of CLT

Revision: D01
Date: 13/03/20
Project Number: OX18034

Prepared for: BRANZ

Project: Research & Development
Project Location: N/A
Prepared by: OFR Consultants
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Project No: OX18034
Revision: D01
Date: 13/03/20

Quality Management

Revision	Date	Comment	Author	QA and Technical Review	Approver
D00	03/02/20	Draft issue	M. Norris	M. Spearpoint	D. Hopkin
D01	13/03/20	To reflect BRANZ comments	M. Norris	M. Spearpoint	D. Hopkin

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1 Purpose

In recent years the construction industry has seen a large uptake in timber products in a shift away from commonly used construction materials such as steel and concrete. This shift toward timber products had been made possible by advances in engineered timber such as cross laminated timber (CLT) and glulam which have higher strengths than traditional sawn timber. The uptake can also be attributed to the global trend of decarbonisation in response to climate change. Compared to other major building materials, timber is often perceived to be the most environmentally friendly due to renewability of wood, low production energy consumption and low levels of pollutant emissions during production [1]. Timber acts as a carbon store, and as such, the construction industry's shift toward engineered timber buildings is seen as a way to create a large carbon sink within the fabric of buildings [2]. Furthermore, following its primary use as structure, there are many secondary uses for timber construction waste which retains its value [3]. In addition to the environmental benefits of engineered timber, the recent uptake can also be attributed to its adoptability in off-site modular construction.

Although the environmental benefits of engineered timber are numerous, there are still concerns over the fire safety of building large buildings using these products. In the context of CLT, these concerns relate to the reaction-to-fire performance, its load bearing capacity during a fire and how the product can be used in a performance-based design environment. In addition, issues have been raised regarding the influence CLT will have on the dynamics of a compartment fire as there may be an increased fuel load and there is a possibility of delamination which may cause secondary flashover which prevents auto-extinction of the fire. As CLT, as an engineered timber product, is a recent technology there is limited history of passive fire protection as applied to this product. Therefore, this document discusses the current passive fire protection methods used for CLT and possible future methods being researched / developed.

This report makes up a package of work OFR Consultants has been contracted to complete for BRANZ Ltd. to provide publishable guidance on methods for the passive fire protection of CLT in New Zealand with reference to methods used in other areas of the world. This report is based on current guidance, regulations and research on the provision of passive protection of CLT in the construction of buildings.

2 Terms and Definitions

2.1 Reaction-to-fire

Reaction-to-fire is a method of classifying the 'early fire hazard' a building material or element by evaluating the contribution of the material to the development and spread of fire. Various properties are derived from standardised tests that fall under the umbrella of reaction-to-fire such as ignitability, heat release, flame spread, and the amount of smoke produced.

Different test methods have been developed in different jurisdictions to assess the reaction-to-fire properties of materials. In New Zealand, the Group Number is a numeric representation of the performance achieved during a fire test to either ISO 9705 [4] or ISO 5660 [5]. Group Numbers range from 1-4, with larger numbers being more combustible, creating a hierarchy for the risk of flame spread over a surface finish based on the measured or predicted 'time to flashover' in the ISO 9705 test.

In Europe, the same general hierarchy exists to assess reaction-to-fire properties of materials called the Euroclass system. While different testing conditions are used to classify reaction-to-fire properties in the Euroclass system, the classifications are considered to be sufficiently similar to the Group

Number requirements and as such are permitted in New Zealand for interior wall and ceiling linings as an alternative to the Group Number system [6]. The Euroclass system is divided into two subsystems; one for construction products not including floors and one for construction products for flooring.

2.2 Fire resistance

Fire resistance is used as a method of classifying the capability of a structure, a part of a structure, or a member to withstand a defined heating regime broadly intended to be representative of the post-flashover phase of a fire. A more in depth discussion is available in chapter 12 of CIBSE Guide E [7]. The fire resistance of a member is intended to mitigate the spread of smoke and fire from one compartment to another and to mitigate structural collapse [8]. Evaluations of a member are determined on its ability to fulfil its required functions for a specific load, fire exposure as evaluated under a standard time-temperature exposure, such as ISO 834-1 [9], for a period of time.

In New Zealand, fire resistance is described by the use of three numbers. Together they give the fire resistance rating (FRR) expressed through the time in minutes for which each three main criteria, structural adequacy, integrity and insulation, are satisfied when the element is subject to the test procedure. The criteria are described as [10],

Structural adequacy:

> *The ability to support a vertical axial load and only applies to loadbearing elements of structure*

Integrity:

> *The ability to prevent the passage of flame and hot gases measured by the creation of a gap or ignition of a cotton pad on the non-fire (unexposed) face*

Insulation:

> *The ability to limit the temperature rise on the non-fire (unexposed) face*

These terms are defined in the test standard AS 1530.4 with the unexposed face sometimes referred to as the 'cold face'.

Similarly, fire resistance is broadly described by three criteria throughout Europe, as set out in Eurocode 1 [11] as,

Stability (R):

> *The ability of a structure to sustain specified actions during relevant fire, according to defined criteria*

Integrity (E):

> *The ability of a separating element of building construction, when exposed to fire on one side, to prevent the passage through it of flames and hot gases and to prevent the occurrence of flames on the unexposed side*

Insulation (I):

> *The ability of a separating element of building construction, when exposed to fire on one side, to restrict the temperature rise of the unexposed face below specific levels.*

2.3 Cross laminated timber (CLT)

CLT is an engineered timber product consisting of sawn timber planks glued together in an orthogonal arrangement. Timber species used for CLT are coniferous, evergreen softwoods, predominantly Spruce, with various amounts of Douglas Fir, Western Larch and Pine depending on availability in the manufacturing region of the CLT. CLT is generally manufactured in large panels several metres in each direction with the individual layer, or lamella, thickness ranging from 10-40 mm [12]. Panels range from thicknesses of 40-300 mm with build-ups generally consisting of three, five, or seven lamellae. CLT panels can be used for walls, floors or ceilings.

When manufacturing CLT both face and edge gluing of the individual planks can be used. However, edge gluing is less common as it increases the cost and complexity of the process. The primary benefit of edge gluing is to reduce the likelihood of gaps being present between the planks that form a lamella. After the application of the adhesive, the assembly is pressed using either hydraulic or vacuum presses and compressed air. Hydraulic presses are more common. However, the press type will depend on the panel thickness and the adhesive used [12].

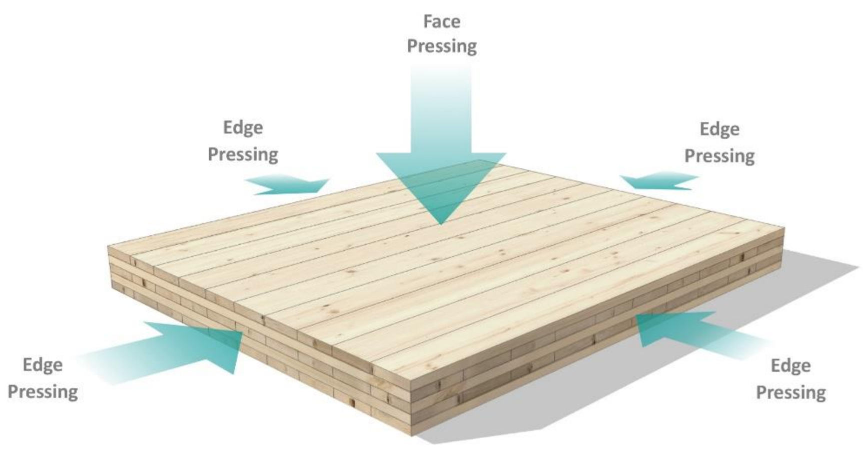


Figure 1. CLT press directions (to be redrawn)

With developments in press technology, which historically only apply vertical pressure (face pressing) to bond lamella, lateral pressure (edge pressing) can be applied during manufacturing, schematically shown in Figure 1, reducing the gap widths to effectively zero without the need for edge gluing [13].

When subjected to fire or elevated temperatures, the exposed face of the CLT panel will char and the adhesive may soften and / or char.

Depending on the orientation of the CLT panel, the loss of carrying capacity of the charred timber or reduced strength of adhesive, there is potential for a lamella of the CLT to delaminate (falling off of lamella) or for portions of the lamella to fall off in a process called char fall off.

The fire resistance properties of CLT are roughly similar to that of solid timber if no delamination or char fall off occurs [14].

2.4 Protection of engineered timber products

The passive protection of timber can generally be achieved with three different methods depending upon the objective[1]: fire retardant coatings, protective lining using boards or impregnation with fire retardant chemicals. Protection with coatings entails the use of intumescent paints or fire retardant coatings, as discussed in Section 5, while the use of protective boards describes the use of combustible or non-combustible boards to prevent or delay the onset of charring. All of these methods of passive fire protection are applicable to CLT panels and used to different extents.

While conducting this review various terms describing the same concepts in relation to protection of timber were found throughout the literature. For clarity and consistency, the terms used within this report are defined as below:

- **Exposed**: Absence of protection or when protection no longer performs its intended purpose. In other literature this is described as unprotected [15].
- **Partially protected**: Lining of the mass timber elements, where the applied protection material cannot mitigate pyrolysis for the full duration of the fire resistance period when subject to the standard time-temperature curve where the fire resistance period is a proxy for the time until burnout of the fire. In other literature this is described as partially encapsulated, partially exposed, or limited encapsulation [15].
- **Encapsulated**: The outer surfaces of the CLT which are suitably lined with non-combustible board, or another form of protection, such that pyrolysis is mitigated for the full duration of the fire resistance period when subject to the standard time-temperature curve where the fire resistance period is a proxy for the time until burnout of the fire. In other literature this is described as fully encapsulated, fully protected, or complete encapsulation [15].

It should be noted that the protection methods are not mutually exclusive. For example, a CLT wall may be provided with a fire retardant and then protected with a layer of non-combustible board. Similarly, a CLT wall may be provided with a coating of intumescent and then protected with non-combustible board provided that there are fire-resistant battens which give enough space for the intumescent to expand.

2.5 Auto-extinction

In order for continued burning of solid timber, an external heat flux must be applied since the flame heat flux from the timber is typically not sufficient to sustain its own combustion [16]. An investigation into the auto-extinguishment of CLT [17] identified three stages: flaming combustion, smouldering combustion and auto-extinguishment. This same investigation concluded that smouldering extinction of CLT occurs when an externally applied heat flux falls below 5 to 6 kW/m^2.

Experimental results have shown critical heat fluxes for piloted ignition of timber in the range of 12-14 kW/m^2 [16] while small and full-scale fire tests on a compartment with exposed CLT [13] found the flaming ignition critical heat flux for Radiata pine CLT, below which flaming auto-extinction occurs, to be approximately 45 kW/m^2. The authors of [14] noted, however, that delamination could lead to secondary flaming and prevent auto-extinction and as such their results should be applied with caution.

These results indicate that the minimum radiant heat flux required for flaming combustion is over seven times greater than that required for smouldering combustion. When timber is still smouldering,

[1] Objectives may be to improve: (a) reaction to fire performance, and / or (b) enhance structural fire performance (fire resistance, where relevant).

there is a possibility that the timber could reignite with an increased air flow across the surface or that continued smouldering combustion degrades the surface further and the extent of the charring reaches a critical depth for structural failure.

2.6 Ventilation controlled vs fuel controlled

Most typical small compartment fires are ventilation controlled, meaning that the size of the ventilation opening, and therefore the amount of oxygen that reaches the fire and the hot gases that can leave the compartment are the primary factors influencing the rate of combustion. Some compartment fires, however, are fuel controlled meaning that the rate of combustion is primarily dependent on the type of fuel and the available surface area of the burning fuel.

The opening factor, Ω, (for enclosures which only have vertical openings) is a key component in the determination of the maximum temperatures achieved in post-flashover compartment fires with only vertical openings and is defined as

$$\Omega = \frac{A_V\sqrt{H}}{A_T}$$

Where:

A_T is the total area of the enclosure including openings [m^2];

A_V is the total area of the vertical openings [m^2]; and

H is the height of the vertical openings [m].

For low opening factors (<0.15 m$^{1/2}$) the compartment temperatures increase as a function of the opening factor. After this limit the compartment temperatures decrease with an increasing opening factor [18].

The vertical opening area of a compartment can also be used to determine the burning rate of the fuel, assuming a ventilation controlled fire, according to the ventilation factor, $A_V\sqrt{H}$, multiplied by a coefficient based on the fuel (typically 0.09 for wood) [16]. This correlation is shown in the first regime of the plot in Figure 2 while the second regime, shown by the horizontal line, represents fuel controlled compartment fires.

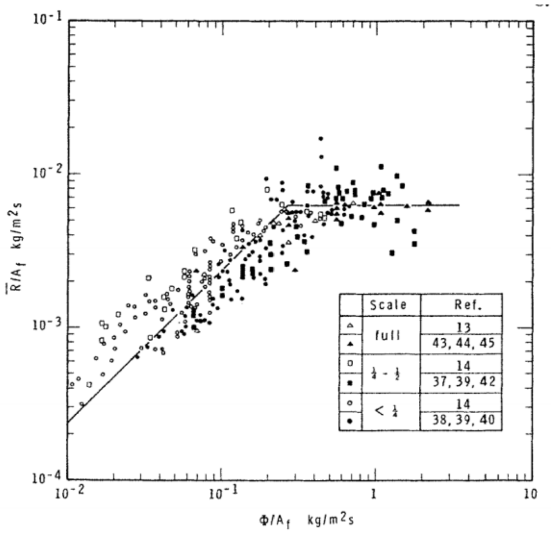


Figure 2. Correlation of experimental data concerning burning in compartment fires [19]

3 Protection strategies for timber structures

3.1 Design for Burnout

The fire protection design of any building is dependent on requirements generally established by governing regulations with the primary aims being to mitigate fire and smoke spread within the structure and partial or full collapse of the structure. Four general outline criteria are described by Buchanan [8] to be considered when determining the level of fire performance that is appropriate. These are:

- Time for occupants to escape from the building,
- Time for fire-fighters to carry out rescue activities,
- Time for fire-fighters to contain the fire, and
- A complete burnout of the fire compartment with no fire-fighter intervention.

The final criterion is arguably the most important for the structural performance of the building. However, design methods and codifications of these design methods are not well advanced.

The most common method of designing for burnout is the time-equivalence principle which assumes that the fire severity is a function of fire load, ventilation and thermal properties of the compartment boundary materials [15]. The severity of a natural fire (ignition to burnout) is expressed as the duration of standard fire exposure that leads to equivalence, often expressed in terms of either: (i) equivalent area under the time temperature curve of the gas phase, or (ii) the equivalent maximum temperature of a structural element and in some cases, (iii) the equivalent absorbed or incident energy.

When modelling a compartment fire in which some or all of the boundaries are constructed of CLT, many factors including the duration of the fire, fire load, charring depths, thermal exposure, and whether the fire is ventilation or fuel controlled, are interdependent and therefore can lead to large propagation of uncertainties in an analysis [20]. Difficulties in estimating the fire severity alone of a compartment made of CLT include determining how the combustible surfaces contribute to the fire load, the opening factor's effect on the fire development and the determination of the assumed mass loss rate of the timber in compartment fires [21].

Estimating the equivalent duration of standard fire exposure for CLT buildings requires knowledge of all of the above factors and the level of protection the CLT is provided with. The level of protection is generally classed as encapsulated, protected, or exposed, as described in Section 2.4. The protection can be provided by non-combustible linings that use gypsum plasterboard, magnesium oxide board or fibrous board; intumescent coating; or wood-based panels such as OSB, particleboard or fibreboard. The mechanisms and suitability of each type of protection is described further in the following sections.

In addition to the criteria for auto-extinction described in Section 2.5, there is the possibility that a compartment fire is not severe enough for the CLT to undergo smouldering combustion. For this to happen, the incident heat flux to any exposed timber must be less than c. 12.5 kW/m^2 (the heat flux for piloted ignition of timber [16]) throughout the combustion of movable combustible fuel, i.e. furniture, fixtures and other contents. This scenario requires a very low fuel load or intervention by active fire prevention.

If the incident heat flux to any exposed timber is below this threshold, the CLT will not become involved in the fire and after the movable combustible fuel is consumed the fire will decay to burn-out. Generally, in compartment fires with one or more exposed CLT surfaces, this is not the case and the incident heat flux from the fire initially fuelled by the movable combustibles to any exposed timber is sufficient to cause the CLT to become involved in the fire. Once the CLT has become involved in the fire, the incident heat fluxes to the exposed timber must decay to under approximately 45 kW/m^2 for flaming combustion auto-extinguishment and then continue to decay to under 5-6 kW/m^2 for smouldering combustion auto-extinguishment. These heat fluxes would include any re-radiation between flaming or hot surfaces after the movable fire load has been consumed and therefore the orientation between exposed surfaces in a compartment may become important.

4 Protective boards

This section of the report describes a variety of protective boards which have either been used in construction or have been the subject of investigation in research experiments for use as a protective lining for timber structures. As such, any materials herein have not necessarily been used in timber construction in New Zealand or elsewhere.

4.1 Gypsum plasterboard

Gypsum plasterboard is a commonly used as a passive fire protection lining for timber structures. Plasterboard is formed of a sandwiched gypsum core between two paper facing sheets. The fire resistance characteristics of gypsum plasterboard stem from its high quantity of chemically bound water (c. 21% by weight) and its free water (c. 3% by weight). This has large implications with respect to gypsum plasterboard's thermal properties as large amounts of energy are required to evaporate its water content before rapid heating of the gypsum can occur.

The properties of gypsum plasterboard are often enhanced using additives such as bentonite or vermiculite. Additives such as these are used to increase the core adhesion, acoustic characteristics, moisture resistance, etc. of the board.

Gypsum plasterboard generally comes in standard sizes and a range of thicknesses. As production and marking of gypsum plasterboards varies across the world and with different manufacturers, in New Zealand fire rated lightweight systems using gypsum plasterboard linings are generally proprietary based on standard fire resistance tests.

Generally, gypsum plasterboard can be classed into three different groups:

- **Type A or regular**: This is the typical plasterboard sold for residential construction. It is not required to have any fire resistance so is usually constructed with low density gypsum and does not benefit from any reinforcement provided by glass fibre or other additives [22]. Regular gypsum boards perform poorly in fire situations relative to enhanced performance boards such as Type F as the gypsum core begins to fall away upon dehydration.
- **Type F or Type X:** Fire rated gypsum boards (Type X in North America and Type F in Europe) are reinforced with glass fibres or other additives such as bentonite or vermiculite to improve their fire resistance by increasing the core adhesion performance at elevated temperatures [14].
- **Special purpose**: These boards are provided with various additives to obtain enhanced fire and/or structural performance over Type X boards, such as Type H or Type R which have improved water resistance and strength, respectively. They are often manufactured in non-standard dimensions to meet market needs [14].

4.1.1 Gypsum plasterboard properties

Plasterboard typically undergoes two dehydration reactions when exposed to fire. The first typically occurs between 80 and 120 °C whereby approximately 75% of the chemically bound moisture content is released and evaporated. Similarly, all the gypsum's free water is also released and evaporated within this temperature range. The second dehydration phase occurs between 200 and 240 °C during which the remaining 25% of chemically bound moisture content is released and evaporated [23], [24].

Several temperature dependent conductivity and specific heat values exist for gypsum plasterboard and have been implemented in the simulation of the behaviour of timber and steel stud walls. An overview of the most common gypsum properties adopted for these numerical models was conducted by Hopkin and the comparisons are shown in Figure 3 to Figure 5 [24]. The comparisons also included less commonly used property values for completeness. The study highlighted the additive heat concept presented by Ang and Wang in which a mathematical formula for the specific heat of gypsum as a function of its moisture content is presented [25].

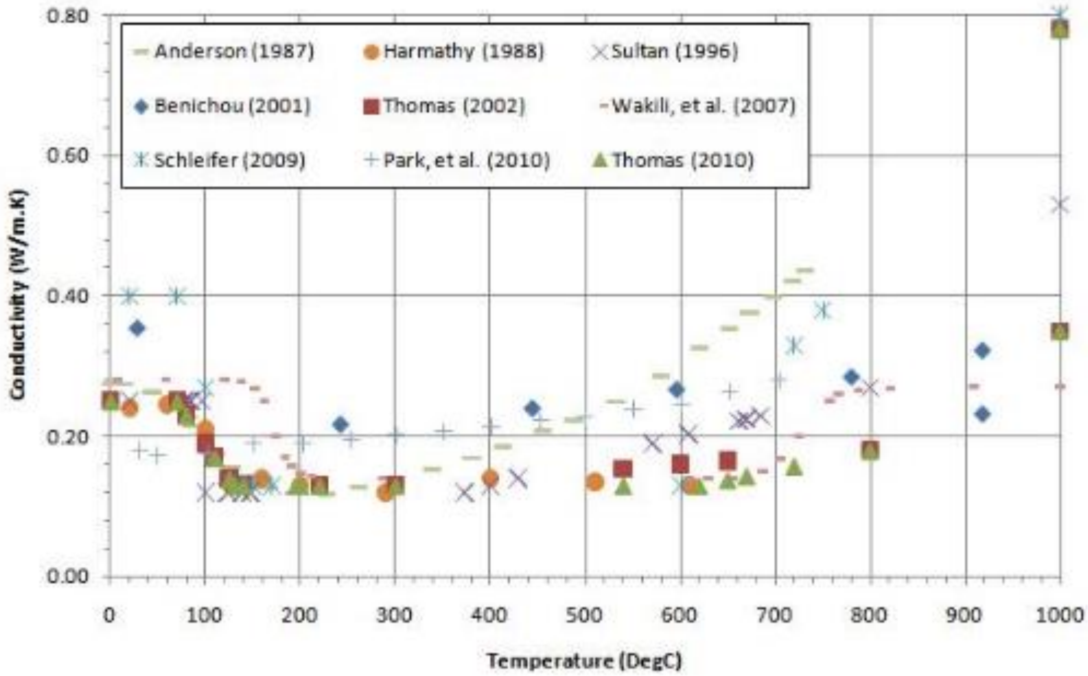
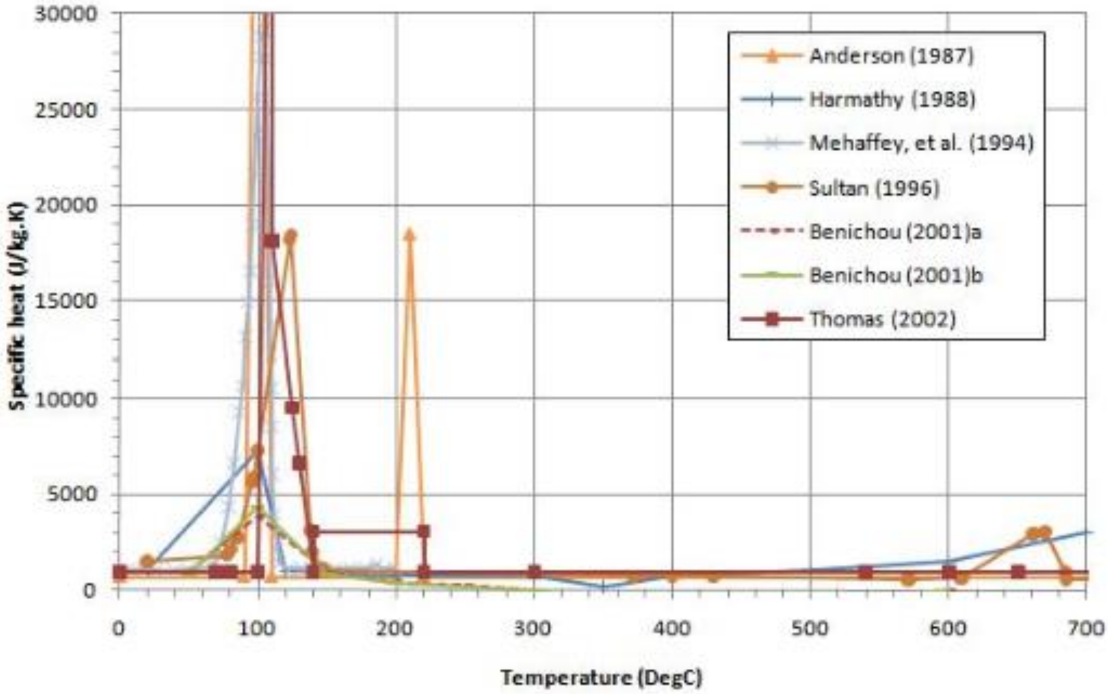


Figure 3. Comparison of temperature-dependent thermal conductivity of gypsum plasterboard



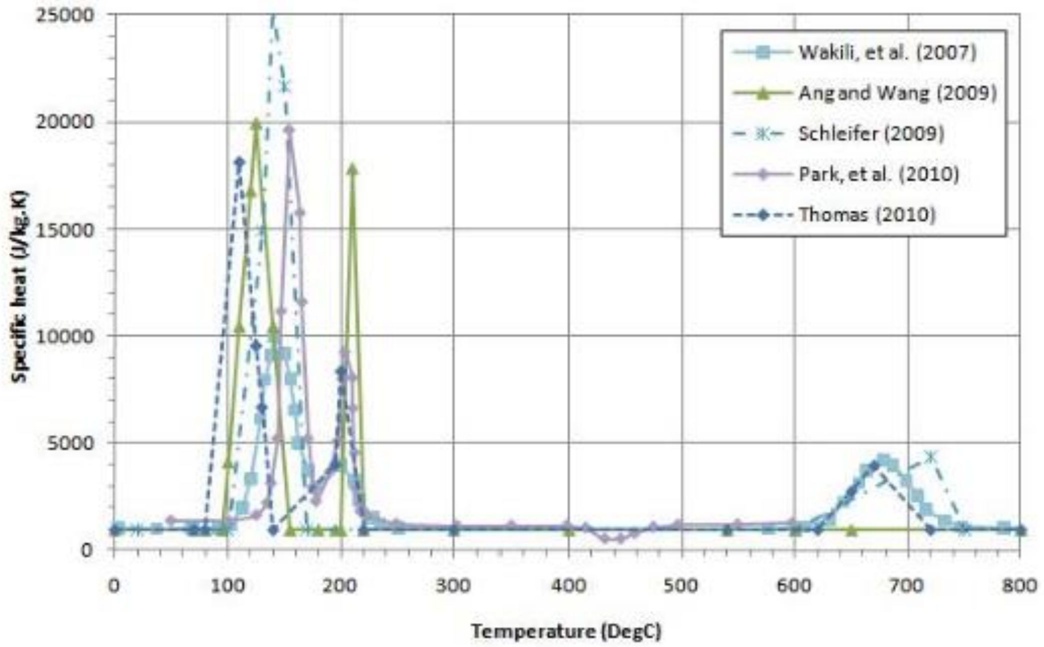


Figure 4. Comparison of temperature-dependant specific heat of gypsum plasterboard

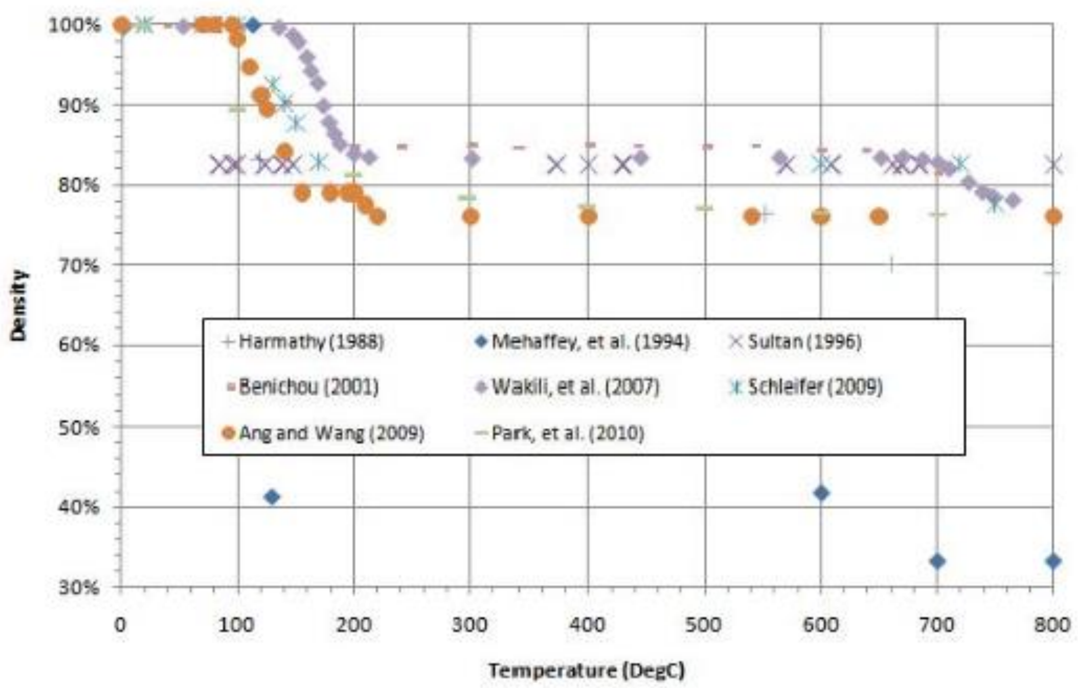


Figure 5. Comparison of temperature-dependant density of gypsum plasterboard

From current gypsum board suppliers in Europe such as British Gypsum [26], thermal conductivities of Type F boards vary from 0.24 W/m.K to 0.30 W/m.K. These values are taken from tests conforming to EN 520. Similarly, thermal conductivities of boards rated for fire protection by Knauf achieve thermal conductivities of 0.24 W/m.K in order to meet specifications for Type F boards according to EN 520.

4.2 Alternatives to gypsum plasterboard

Currently, gypsum plasterboard dominates the market as the primary protective board used for the lining of CLT. However alternative types of boards have been investigated and used for fire protection purposes within the construction industry.

4.2.1 Fibrous board / Gypsum fibre board

Fibrous board products are generally used as interior wall, ceilings and linings for their high stability and non-combustibility. They are made from recycled paper fibres mixed with gypsum complying with EN 15283-2 [27]. The mixture is hydrated and formed into boards at high pressures before being dried and coated with a water repellent. Gypsum fibre boards generally have higher densities that gypsum plasterboards. When exposed to a standard heating curve using a radiant heat source intended to reflect ISO 834-1 [9] heating in a furnace, onto a horizontal surface equivalent to a floor gypsum, fibreboards performed similarly to gypsum plasterboard and no significant difference was observed with regard to thermal behaviour [28]. Since the test specimen was on a horizontal surface, fall off was not a relevant factor.

4.2.2 Gypsum particleboard

Gypsum particleboard (GPB) consists of primarily natural gypsum and residual or recycled wood particles pressed into panels. The manufacturing process generally utilises industrially disposed gypsum which is a by-product of many chemical processes [29], [30]. When tested to ISO 5660-1, GPB made with *P. massoniana* and *Eucalyptus sp.* showed lower peak heat release rates, smoke production rates and CO yields than other wood-based panels also tested to ISO 5660-1 [31].

4.2.3 Magnesium oxide board

Magnesium oxide (MgO) board is a versatile mineral board of magnesium cement cast into thin cement panels and used in residential and commercial buildings as wall and ceiling covering material or as substrates for intumescent coatings and insulating systems. General uses of the board include fire resistance, mould and mildew protection, and sound control applications. Bench-scale experiments have shown that 12 mm thick MgO board delayed the charring of a CLT panel by 18 min and 15 min at incident heat fluxes of 50 kW/m^2 and 65 kW/m^2 respectively [32].

4.2.4 Calcium-silicate boards

Calcium-silicate boards are manufactured from a mixture of Portland cement, fine silica, cellulose fibres and various fillers to improve durability, toughness and moisture resistance. Calcium-silicate boards have been increasingly used to protect light steel frame walls for their improved physical and thermal properties in addition to their lightweight, economic, and impact resistant properties [33]. A fire resistance experiment conducted on 12 mm thick calcium-silicate boards on cold formed steel walls found that they exhibited 'explosive' spalling at elevated temperatures [34]. However, spalling was not observed in fire tests with 20 mm thick boards [33]. This difference was attributed by the study authors primarily to the thickness of the board.

4.2.5 Cement boards

Cement boards are a mixture of cement and water and reinforced with either fibres or particles. The mixture is then formed into sheets, pressed and dried. When tested under a cone calorimeter to ISO 5660-1 and exposed to an incident heat flux of 75 kW/m^2, build-ups of 1 and 2 layers of 12.7 mm of cement board took 13.83 min and 14.32 min respectively for the average temperature change at the interface of the board and a plywood substrate to reach 250 °C [35]. When tested to CAN/ULC-S135 with a large holder and exposed to an incident heat flux of 50 kW/m^2, two layers of 12.7 mm thick cement board took approximately 34 min for the same criterion. When tested in an intermediate-scale furnace, a single 12.7 mm thick cement board achieved the same criterion in 16 min.

4.2.6 Gypsum concrete boards

Gypsum concrete can be made with either coarse concrete aggregates or porous natural and synthetic materials applied as aggregates to achieve normal or lightweight boards, respectively. When tested under a cone calorimeter to CAN/ULC-S135 with a large holder and exposed to an incident heat flux of 50 kW/m^2, 25 mm and 29 mm thick gypsum concrete coverings took approximately 25 min and 47 min respectively for the average temperature change at the interface of the board and a plywood substrate to reach 250 °C [35]. When tested in an intermediate-scale furnace, a 25 mm and 38 mm thick gypsum concrete material achieved the same criterium in 28.8 min and 55.1 min, respectively.

Gypsum concrete particleboard has also been shown to have a thermal conductivity of 0.596 W/m.K. The thermal conductivity varies from 98% to 148% greater than that of gypsum plasterboard however the addition of cement contributes to the board provides protection against moisture making it a suitable alternative to gypsum plasterboard in situations where moisture protection is required [36].

4.2.7 Ceramic fibre board

Ceramic fibre board is made from refractory fibres and binders with low organic content which are vacuum processed into boards which can be manufactured in various densities and temperature grades to suit application requirements. The thermal conductivities of ceramic fibre boards have been collected from various manufacturers including North Refractories [37], Morgan Thermal Ceramics

[38], KT Refractories [39], PAR Group [40], IMS Insulation [41], Ceramaterials [42], Geenergy [43] and Pyrotek [44]. The temperature dependant thermal conductivities of the boards vary between manufacturers and within manufacturer specification sheets depending on the additives used. The thermal conductivity of ceramic boards increases with increased average temperature of the board as shown in Figure 6.

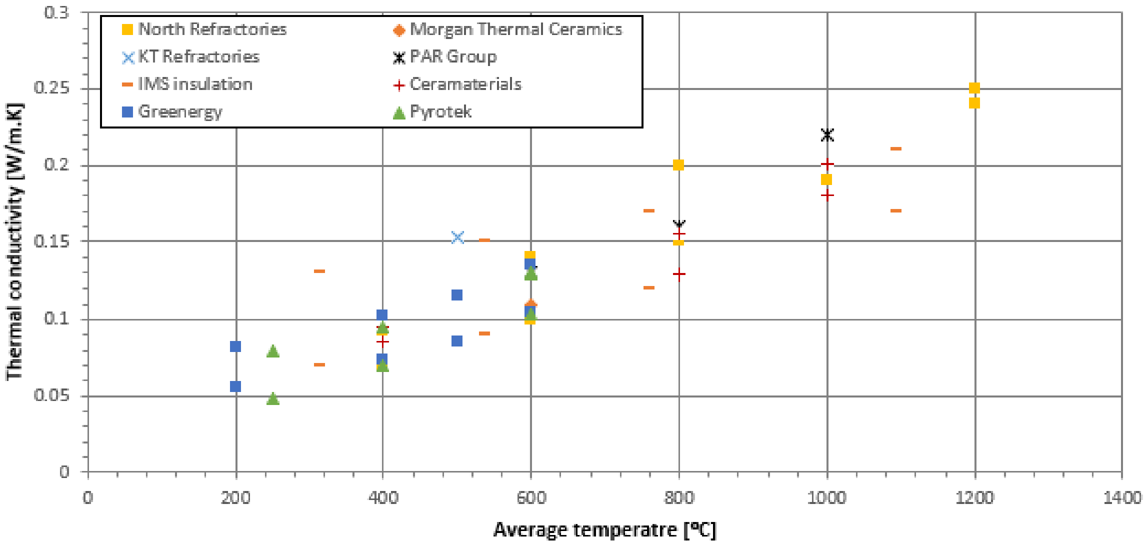


Figure 6. Temperature dependant thermal conductivities of ceramic fibreboard as given by manufacturers

4.2.8 Hemp and clay boards

Currently there is limited fire protection design data on clay and hemp boards as they are relatively immature technologies. However, they are of interest for their sustainability. Although there is currently no product standard at the European level, research has been conducted to determine the fire resistance of different hemp and clay boards in comparison to Type X gypsum plasterboard. When exposed to irradiance levels of 50 kW/m^2 for 20 min and 75 kW/m^2 for another 20 min, 15 mm thick Hemp FK (dry method hemp fibreboard covered with Kraft paper) and 22 mm thick Clay G22 (consisting of clay, hemp shives and an inorganic binder) provided a protection time of 28.1 and 37.5 min, respectively, as measured by the temperature of the interface between the board and the timber reaching a value of 270 °C [45].

4.3 Wood-based protective board

The low thermal conductivity and slow charring rate of wood products may provide protection to the underlying material [46]. Types of wood-based panels include particleboard or fibreboard, plywood and solid wood panelling. The contribution to fire resistance and the contribution of the wood-based panelling to the fire depend on the type of wood-based panel used. Regardless of the type of wood-panel used, the panel thickness is an important factor in determining its contribution to fire resistance and thus fire protection ability [46], [47]. It has also been determined that wood-based products and gypsum plasterboards have similar fire protection ability however their reaction-to-fire varies greatly and although coatings exist capable of reducing different reaction-to-fire parameters to reach the highest European and national fire classifications [48] the coating's influence is minor in a fully developed fire [49].

4.3.1 Wood-Based protective board properties

The fire protective behaviour of wood-based boards has been researched extensively, often to verify their use in the component additive method to calculate the separational fire resistance of wood assemblies or to gain input data for analytical calculations. Figure 7 and Figure 8 are results of a literature review [46] of data from two studies [50] (in Swedish) conducted on wood-based panelling.

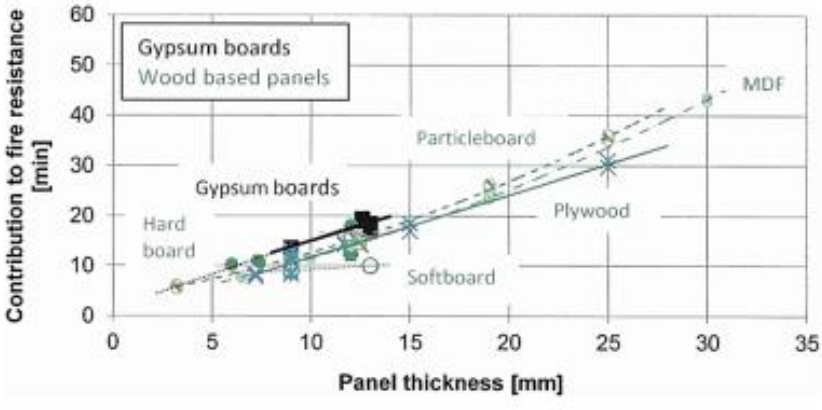


Figure 7. Effect of panel thickness on the contribution to fire resistance of different wood-based panels and gypsum boards [46]

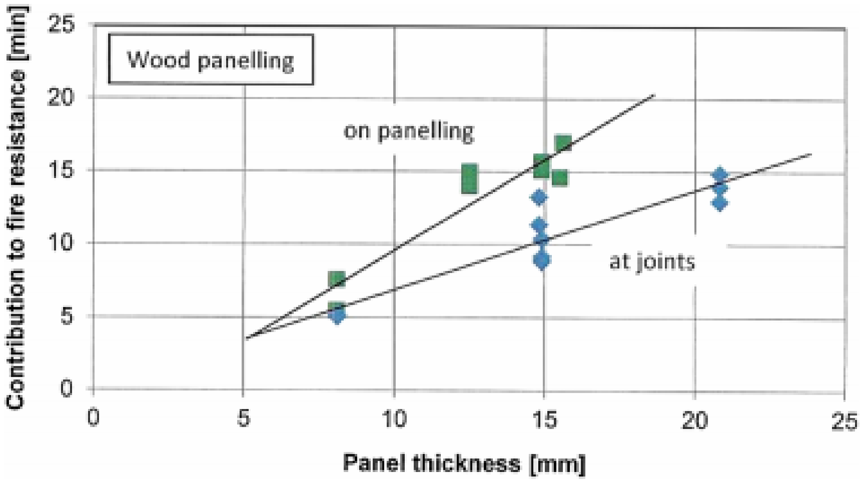


Figure 8. Contribution to fire resistance of solid wood panelling both at joints and on panelling [46]

The data clearly shows a strong relationship between panel thickness and the contribution to the fire resistance of the wooden panel. The study also found that density has a minor role within the range of 500-700 kg/m^3 [46] representing the majority of wood products.

4.4 Compartment fire experiments

The importance of providing the appropriate level of protection to exposed timber in compartments and the major effect delamination of CLT can have on compartment fires becomes apparent upon examination of experimental results with natural fires.

The Fire Protection Research Foundation (FPRF) has completed six full-scale fire experiments on CLT compartments to determine the impact on heat release rate and fire duration of exposed CLT intending to inform the use of exposed CLT within high-rise buildings. The initial observations on the test results are presented below [51].

Test compartments were 9.1 m long, 4.6 m wide, 2.7 m high with a single door opening of either 1.8 m x 2 m or 3.6 m x 2 m. The fuel load was 550 MJ/m^2, the CLT panels were 175 mm thick, five-lamella spruce-pine-fir.

Table 1. Summary of FPRF experiments

Experiment	Protection*	Opening	Flashover [min]	Peak HRR [MW]	Comments
1	Encapsulated Three layers Type X plasterboard	Small wall opening	14.9	9.5	Two layers remained on ceiling Three layers remained on wall No significant CLT charring
2	Encapsulated Two layers Type X plasterboard	Large wall opening	15.3	12.5	Most protection remained on ceiling, but face layer fell off of the centre Two layers remained on walls Some charring on the ceiling
3	One long wall exposed Three layers on ceiling Two layers on wall	Large wall opening	14.0	14.5	Char fall off of the first and second lamella of exposed CLT occurred and resulted in increased HRRs Protected walls had evidence of charring up to 20 mm depth
4	Ceiling exposed Three layers on wall	Small wall opening	12.0	13.3	Char fall off of two lamellae of the CLT on the ceiling increased the HRR Some limited charring behind the gypsum protection

5	One long wall exposed Three layers on walls and ceiling	Small wall opening	18.0	9.5	Char fall of the first and second lamellae of exposed CLT resulting in increased HRR Gypsum protection then failed on opposite wall Gypsum began to fall from ceiling HRR accelerated up to 9-10 MW Fire extinguished as HRR grew past 10 MW
6	Long wall and ceiling exposed Three layers on walls	Small wall opening	16.0	13	CLT protection began to fail around 60 min Extinguished and charring was on all walls with no protection visible

***** A layer of protection consisted of 15.9 mm thick gypsum plasterboard screwed directly into the CLT at a spacing of every 300 mm.

A further review of 20 fire experiments with exposed CLT has been conducted [52]. Of the 20 experiments, 13 did not exhibit auto-extinction. In these 13 experiments, the fire behaviour was characterised by continued burning or peaks and troughs of HRR (generally caused by delamination). In the seven experiments characterised by sustained burning, multiple surfaces were exposed, and the sustained burning of the exposed surfaces continued until extinguishment by hose streams.

Both the further review and the FPRF experiments note the increased likelihood of secondary flashovers caused by delamination of CLT. In addition to this, the FPRF experiments highlight the effect of the opening factor as Test 3 and Test 5 both consisted of one exposed wall with the key difference being the size of the opening. While Test 3 exhibited auto-extinction, Test 5 exhibited delamination of CLT, a secondary flashover, and the failure of gypsum plasterboard and consequently needed to be extinguished by hose streams prematurely.

5 Fire-retardancy

Fire retardant coatings and treatments are often provided to timber in construction in order to improve the reaction-to-fire properties of the timber. There are three proposed mechanisms for providing fire retardancy [53]:

- Reduce the flow of heat to the fuel surface to prevent further combustion, this includes forming a glaze or foam to insulate the material surface.
- Quench the flame provided that the fire-retardant releases radicals at temperatures that inhibit the propagation of flaming combustion.
- Modify the thermal degradation process of the material so that the temperature at which pyrolysis occurs is lower and a greater amount of char will form, decreasing the amount of volatile gases which become involved in the fire.

The third method is generally the most common mechanism in commercial products. However, in all probability, most fire retardants will use a combination.

5.1 Fire retardants and treatments

Various types of treatment exist which achieve fire retardancy of the wood to various levels of success and a review of the European classes to reaction-to-fire concluded that the highest European and national fire classifications for combustible products (Euroclass B) can be reached with treated wood products [47]. Fire retardants can be applied to both CLT panels and where protective wood-based boards are being used as a lining. However, no retardants exist which can classify either CLT or the wood based boards to Euroclass A [54].

Although enhanced reaction-to-fire properties are attainable, fire retardants have been known to increase the degradation of the wood and, as a result, decrease the strength of the timber [55].

For interior applications, where leaching of the fire retardant is not deemed an issue, water-soluble inorganic salts are the common flame retardants, the chemical make-up of which can be modified to develop optimal flaming, smouldering, and smoke reduction performance [56], [57]. However, excessive levels of flame-retardant treatments can increase smoke production.

Often fire retardants must be maintained or reapplied every few years and often present a wider environmental impact in both their production and their impact on the recyclability of the timber at the end of the building life cycle. Within the UK, 84% of schemes with exposed timber required treatment of that timber to improve its surface spread of flame properties, of those that did not, most were small low-rise schemes [2].

Flame-retardant treatments tend to have minimal impact on the charring rates of timber [56]. Additionally, although fire retardants are able to achieve the highest possible reaction-to-fire ratings for combustible material, Euroclass B, it is of minor influence where fire resistance is concerned as it has been found that their effect in a fully developed fire is minimal.

5.2 Intumescent coating

Intumescent coatings are widely used within the steel industry for the protection of load bearing elements during fire. The use of traditional halogenated flame retardants has been limited in response to concern about the possible formation of extremely toxic halogenated dioxins [58]. In their place, more environmentally friendly and less toxic phosphorus based intumescent coatings have become a major focus of research [59]. With the recent increase in the number of proposed tall timber buildings caused by the advance of timber technologies, intumescent coatings have been proposed as innovative solutions for the protection of timber elements.

Intumescence is defined as the swelling of certain substances when exposed to enough heat, thereby increasing the coatings volume and decreasing its bulk density. The reactive material swells to form a multicellular layer, or thick porous char, which acts as a thermal barrier which can effectively protect the substrate against rapid temperature increase [60]. Efficiency of the intumescent as a thermal barrier is determined by the thickness, coherence and porosity of the char. Thermal barriers such as intumescent paints are also capable of acting as gas barriers which limit both the access of pyrolysis gases from the intumescent coating's substrate to the movable fire load and oxygen access to the substrate surface [61].

Intumescent coatings generally contain three 'active' components bound together by a binder [62]. The three 'active' components are an acid source, a carbon source and a blowing agent as described below [63]:

Acid source:

> Usually containing or creating a poly phosphoric acid or other acid which promotes char formation such as ammonium polyphosphate or a mineral acid.

Carbon source or carbonizing substance or carbonizing agent (carbonific):

> These are generally char forming polymers or polyols. These substances are picked to have a considerable number of carbon atoms. The thermal decomposition of these results in the formation of carbonaceous material having many hydroxyl groups. A carbon rich polyhydric compound that will influence the amount of char formed and the rate of char formed.

Blowing agent:

> The most common blowing agent used in intumescent coatings is melamine. The blowing component decomposes and releases non-flammable products such as CO_2, H_2O or NH_3 [62]. They expand the char and form the swollen multicellular layer.

The thermal properties of the intumescent are fully dependent on the chemistry of the intumescent and the rheology (expansion phase and viscoelasticity of the char). However, the addition of small amounts of synergistic compounds to the formulation of the intumescent may dramatically enhance performance by modifying the chemical and physical behaviour of the intumescent char [63].

Research has been conducted examining transparent intumescent fire-retardant coatings for wood substrates to increase the aesthetic appeal of intumescent coatings for fire protection [64]. Unlike traditional intumescent coatings, transparent intumescent coatings are prepared by bonding reactive flame retardants such as magnesium phosphate ester directly onto the backbone of the polymer matrix rather than physically blending the flame retardant in which have traditionally caused the opacity of the coating [65].

Other possibilities for coatings used to protect CLT include ceramic coatings which have been shown to enhance light and moisture resistance in addition to increased fire resistance through its water crystallisation in a similar manner to gypsum boards [66]. Nanocomposite coatings could also be used to improve the fire performance of wood-based products as intumescent polymer-clay nanocomposites have been applied to protect both polymers and steel [67]. Similar studies for wooden or wood-based products are currently not available.

5.2.1 Intumescent coating properties

Thermal conductivity is the primary influencing parameter on the effectiveness of an intumescent system. If the structure of the intumescent char is appropriate (i.e. the morphology and distribution of the voids within the char) then the thermal conductivity will be low and the heat transfer across the char will be limited [63].

Although the reaction of intumescent coatings varies greatly depending on their make-up, generally the coatings will react to form char and swell around 250 °C. Upon further heating (temperatures up to 350 °C), the char will increase in porosity as well as volume. At higher temperatures (400 to 600 °C) the char begins to degrade while its rate of expansion remains constant [68].

The effectiveness of intumescent coatings can be increased with the addition of a thin metal sheet on top of the intumescent coating which acts as an additional gas barrier to prevent pyrolysis gasses from contributing to the fire load [69]. However, this is general advice on the use of intumescent and not specifically for the protection of CLT.

A study of the reaction to fire of epoxy based intumescent coatings was conducted using the hot disk method for temperatures up to 800 °C and observations and trends have been suggested to extend to other intumescent systems, [70], [71]. Generally, thermal conductivity values (shown in Figure 9 [71]) increase at lower temperatures until the glass transition temperature is reached where it stabilises. Then at approximately 200 °C, coinciding with the formation of char, the thermal conductivity decreases rapidly. At higher temperatures (above 370 °C), the thermal conductivity increases again due to the shrinkage of the char layer and then increases steadily above 500 °C [72].

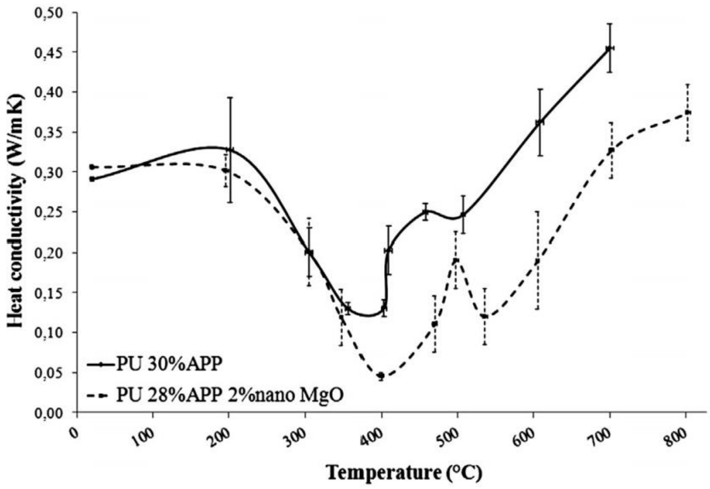


Figure 9. Temperature dependant heat conductivity of epoxy based intumescent

Timber samples uncoated or coated with three different dry film thicknesses (DFT), 0.5 mm, 1.3 mm and 2.1 mm, of a commercially available solvent-based intumescent coating were tested at a constant incident radiant heat flux of 50 kW/m^2 for 60 minutes using the H-TRIS fire test method. The study concluded [73]:

- Time-to-ignition of the timber is influenced by the presence of the initial applied thickness of the intumescent coating.
- The 1.3 mm and 2.1 mm coatings prevented surface ignition of the timber throughout the duration of the test.

- Intumescent coatings seemed to delay the onset of timber charring with the delay being proportional to the DFT of the coating.
- Intumescent coating seemed to reduce the average charring rate after the initiation of charring when compared to that of exposed timber.

5.3 Adhesive types

As discussed in Section 4.4, if a protective board detaches or a lamella of CLT delaminates or experiences char fall off, the charring of the CLT panel or assembly will transition to an increased rate. For this reason, the types of adhesive used in the manufacture of CLT is crucial in the determination of the charring rate and thus the protection value of the CLT.

Standards in both the United States and Canada require CLT adhesives to be evaluated for heat performance in accordance with PS1 [74], the intent of which is to determine if the adhesive will exhibit heat delamination characteristics. If the adhesive fails within the specified test criteria, the CLT manufacturer is expected to consult the adhesive supplier and authority having jurisdiction (AHJ) to provide appropriate strategies in product manufacturing and / or the end use recommendations for the fire protection design of CLT [75].

The Engineered Wood Association and ANSI have published a standard for performance rated CLT which requires the use of the compartment fire test (CFT) to evaluate the performance of adhesives used in CLT. The test requires an unprotected CLT floor-ceiling slab to sustain applied loading during a specified fire exposure period of 240 min without experiencing char fall-off which results in fire regrowth during the cooling phase of a fully developed fire [76].

Common adhesives used in CLT production include phenolic adhesives, such as phenol-resorcinol formaldehyde (PRF), emulsion polymer isocyanate (EPI), or one-component polyurethane (PUR) [12]. PUR is a common adhesive type used in Europe for CLT. However, it should be noted that not all variations within an adhesive type will conform to relevant standards including, but not limited to, fire safety, toxicity, and environmental standards.

PUR type adhesives are also known to have lower softening temperatures than adhesives such as melamine-urea-formaldehyde (MUF) and CLT manufactured with PUR adhesives are then more likely to delaminate when exposed to high temperatures [77], [78]. A comparison of shear strengths of various adhesives at different temperatures is shown below in Figure 10.

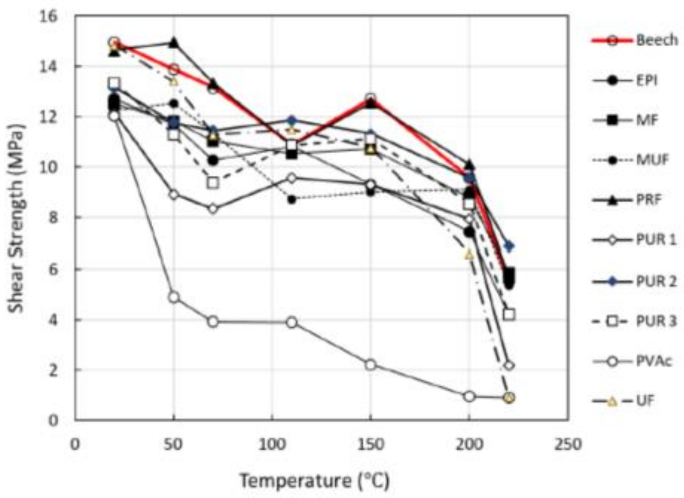


Figure 10. Shear strength of different adhesives compared with solid Beech wood according to EN 302-1 versus temperature [79]

6 Design methods for protected timber structures

6.1 K-class

Within Europe, K-classes are used to determine the protection of a material used as a covering when charring of the substrate should be avoided. For this reason, K-classes are primarily used for load bearing structures. K-classes are defined in EN 13501-2 [80] to be tested in accordance with BS EN 14135 [81]. The K classification is separated into K1 and K2, K1 is used for a classification period of up to 10 min for ceilings while K2 is classified as 10, 30, and 60 min for walls and floors. For both classifications, the protective boards are tested with a chipboard substrate and must demonstrate the covering protection against ignition, charring and other damage to the substrate for prescribed times in full-scale furnace testing. The main assessment parameter for K-class testing is that the average temperature of the unexposed side of the board must not exceed the initial temperature by 250 K and the maximum temperature at any point on the unexposed side of the board must not exceed the initial temperature by 270 K. As the temperature behind the protective panel at various time intervals is the primary assessment criteria, the K-classes focus primarily on fire resistance with less attention paid to reaction-to-fire. This gives a greater opportunity for wood-based lining products to be used as means to provide fire protection to engineered wood panels [46]. K-classes can be used as the start time of charring but contain an extra margin of safety.

6.2 Delay of onset of char

As an alternative to the K-class, the calculation of the delay of onset of char provided by typical wood-based boards and gypsum plasterboard can be calculated for timber frame wall and floor assemblies. Within this method, if CLT is protected it does not char from the outset of the fire. Different charring rates are applied to CLT depending on whether it is initially protected or unprotected from direct fire exposure. If the CLT is protected, charring will start more slowly than that of initially unprotected CLT. If the protection falls off, charring will occur at a much higher rate than that of initially unprotected CLT.

Eurocode 5 provides a calculation for the time to the onset of charring of a wooden substrate protected by wood-based boards and gypsum plasterboards Type A, H or F.

For wood-based panels the time to the onset of charring of the timber is taken as the failure time of the board, t_f. This is given by:

$$t_f = \frac{h_p}{\beta_0} - 4$$

Failure times of Type A or Type H gypsum plasterboard are found from:

$$t_f = 2.8\, h_p - 14$$

where

- h_p is the total thickness of the lining [mm]; and
- β_0 is the one-dimensional charring rate.

The failure time of gypsum plasterboard Type F is determined with respect to the thermal degradation of the board, determined based on tests, and the pull-out failure of the fasteners due to insufficient penetration length into unburnt wood. The failure time with respect to the pull-out of fasteners is given by [82]:

$$t_f = t_{ch} + \frac{l_f - l_{a,min} - h_p}{k_s\, k_2\, k_n\, k_j\, \beta_0}$$

where

- t_{ch} is the time to the onset of charring;
- l_f is the length of the fastener;
- $l_{a,min}$ is the minimum penetration length of the fastener into unburnt wood (taken as 10 mm);
- k_s is the cross-section factor for the width of timber frame member, values are given in table C1 of Eurocode 5;
- k_2 is the insulation factor of the protective board based on the joint configuration as given by equations C.3 and C.4 of Eurocode 5;
- k_n is given as 1.5 in Eurocode 5 as a factor to convert the irregular cross section of the timber frame member into a notional rectangular cross-section; and
- k_j = 1.0 and 1.15 for panels not jointed over the timber member and panels jointed over the timber members, respectively.

Test methods for the thermal degradation of the protective boards are given in BS EN 1363-1 [83], BS EN 1365-1 [84] and BS EN 1365-2 [85] which should be used to determine the failure time of the protective boards due to thermal degradation.

6.3 Component additive method

The component additive method (CAM) was developed in Canada and is designed to determine the fire rating of light frame wood floor, roof, and wall assemblies assuming that a protective time can be assigned to the type and thickness of the protective board as well as the framing and other factors of the assembly. An assembly consisting of two or more separate protective boards then has a rating greater than or equal to that of the sum that of the protective boards [20]. The key factors in the component additive method are the start time of charring of the timber and the fall-off time of the protective boards. The start time of charring is the protection time provided by each layer depending on the thickness and density of the material, with positioning coefficients to account for the effects of the preceding and succeeding layers. The protection provided by the boards also depends on the thermal insulation, the ability of the lining to remain in place and not fall-off after dehydration, the lining's resistance to shrinkage, and the ability of any core material to resist ablation from the exposed fire side. The fall-off time of the boards depends on fastener spacing and length, and the thermal degradation of the board. Screws with an anchorage depth of 10 mm into un-charred wood are assumed to mitigate against protective board fall-off.

The thermal degradation of protective boards also results in fall-off of the board. However, the thermal degradation and other properties of protective boards can vary between different products and within different product lines.

6.3.1 North American CAM

The International Code Council (ICC) recently approved a set of proposals to allow tall wood buildings as part of the 2021 International Building Code (IBC) with various restrictions on their fire resistance ratings [86]. Previously, the use of CLT and other mass timber elements in the USA and Canada in high-rise buildings were considered deviations from the local and international standards and required an alternative solution. This alternative solution was generally achieved through encapsulation [52], [87], [88]. The principle is to keep the timber substrate below its charring temperature (approximately 300 °C) for the full duration of the fire resistance period when subjected to the standard time-temperature curve [89]. The protection provided to the CLT is determined with the CAM method.

The North American CAM method uses times based on empirical correlations taken from ASTM E119 [90] tests of assemblies with ratings ranging from 20-90 min.

Table 2. Protection times provided by different materials in the North American CAM

Board type	Thickness [mm]		Protection time [min]
Douglas fir plywood, phenolic bonded	9.5		5
	13		10
	16		15
Type A gypsum board	9.5		10
	13		15
	16		20
Type X gypsum board	13		25
	16		40
Two layers Type A gypsum board	9.5	9.5	25
	13	9.5	35
	13	13	40

6.3.2 Eurocode 5 (EN 1995-1-2)

A component additive method, similar to that used in North America, is utilised in Eurocode 5 [47] for the fire separation function of a wall or floor assembly. The fire separation function (for evaluation of integrity and insulation) provides a means to determine the protection time expected to be provided by a lining build-up. It is calculated as the sum of the contribution to fire resistance from each layer of material. The Eurocode component additive method differs from the North American approach as it includes consideration of different paths for heat transfer and modifications to include the impact of the layer behind and in front of the of the panel through a position coefficient.

The method requires that the time it takes for the temperature on the side of the assembly not exposed to fire (the insulation time, t_{ins}) to increase by an average of 140 K over the entire board or 180 K at a single point is greater than or equal to the required fire resistance period for the assembly, t_{req}.

$$t_{ins} \geq t_{req}$$

The insulation time is the sum of the contributions of the individual layers which are dependent on the inherent insulation value of the layer, $t_{ins,0}$, the position of the layer with respect to the layers preceding and backing it, k_{pos}, and a joint coefficient to account for the influence of joint configurations, k_j, such that:

$$t_{ins} = \sum_{i} t_{ins,0,i} k_{pos} k_j$$

The inherent insulation value of panels, $t_{ins,0}$, varies with the type, density and thickness, h_p, of the panel according to the values shown in Table 3. The values correspond to the contribution of a single layer to fire resistance without any influence of the previous or following layers (i.e. without consideration of position in the overall assembly). It is the average time for the average temperature rise over the entire board to exceed 140 K or for a single point, 180 K, when exposed to the standard fire.

Table 3. Insulation values

Panel Type	Panel Density [kg/m³]	$t_{ins,0}$ [min]
Plywood	≥ 450	$0.95 \times h_p$
Particleboard and fibreboard	≥ 600	$1.1 \times h_p$
Wood panelling	≥ 400	$0.5 \times h_p$
Gypsum plasterboard Types A, F, R and H	N/A	$1.4 \times h_p$

Tabulated data for position coefficients is also included in Eurocode 5 for wall and floor assemblies with protective boards made of one or more layers of wood-based panels or gypsum plasterboards and void or insulation filled cavities.

This design method is based upon input data for a limited number of wall assemblies and covers and therefore provides a calculation method for a limited amount of timber assembly build-ups. The method is not included in the UK national annex as one of the usable informative annexes of Eurocode 5 [91] and as such this method is not used in the UK.

6.3.3 Improved method

An improved method to the CAM method described in Eurocode 5 has been developed based on experimental results and finite-element thermal analysis and is described by Östman *et al*. [92]. This method can theoretically consider an unlimited number of layers of gypsum plasterboards, wood panels, or a combination of the two in an assembly. The method is like that described in Eurocode 5 in that the total fire resistance is the sum of the contributions of the different layers and considers the possible heat transfer paths. The total fire resistance is given by:

$$t_{ins} = \sum_{i=1}^{i=n-1} t_{prot,i} + t_{ins,n}$$

The protection time of the individual layers, $t_{prot,i}$, is described by the inherent protection value of the layer, $t_{prot,0,i}$, two position coefficients to account for the influence of the preceding layer and the backing layer, $k_{pros,exp,i}$ and $k_{pros,un\,exp,i}$. A correction time, Δt_i, is also included for layers protected by fire rated gypsum plasterboard and a joint coefficient, $k_{j,i}$, is included for the effect of joints. Thus

$$t_{prot,i} = \left(t_{prot,0,i} \times k_{pros,exp,i} \times k_{pros,un\,exp,i} + \Delta t_i\right) \times k_{j,i}$$

The insulation time of the individual layers, $t_{ins,n}$, is described by the inherent insulation value of the layer, $t_{ins,0,n}$, a position coefficient to account for the influence of the preceding layer, $k_{pros,exp,n}$. A correction time, Δt_n, is also included for layers protected by fire rated gypsum plasterboard and a joint coefficient, $k_{j,n}$, is included for the effect of joints. Thus

$$t_{ins,n} = \left(t_{ins,0,n} \times k_{pros,exp,n} + \Delta t_n\right) \times k_{j,n}$$

The inherent insulation value is defined in the same way as in Eurocode 5. However, these values have also been assessed via finite element thermal simulations.

The inherent protection value is defined as the time until loss of the fire protective function, in a similar manner as for evaluation of fire-protective boards of load bearing timber structures in accordance with EN 13501-2. The contribution to the fire protection of the board is determined by the time taken for the average temperature rise over the whole substrate (tested as 19 mm thick particleboard) is limited to 250 K or for a single point, 270 K, when exposed to the standard fire. The inherent protection time is similar to the start time of charring given in Eurocode 5. However, the temperature criteria are slightly lower and therefore more conservative.

Table 4. Basic insulation and protection values for different materials

Material	$t_{ins,0,n}$ [min]	$t_{prot,0,i}$ [min]
Gypsum plasterboard, gypsum fibreboard	$24 \times \left(\frac{h_i}{15}\right)^{1.4}$	$30 \times \left(\frac{h_i}{15}\right)^{1.2}$
Solid timber, CLT, LVL	$19 \times \left(\frac{h_i}{20}\right)^{1.4}$	$30 \times \left(\frac{h_i}{20}\right)^{1.1} \leq \frac{h_i}{\beta_0}$
Particleboard, fibreboard	$22 \times \left(\frac{h_i}{20}\right)^{1.4}$	$33 \times \left(\frac{h_i}{20}\right)^{1.1} \leq \frac{h_i}{\beta_0}$
OSB, plywood	$16 \times \left(\frac{h_i}{20}\right)^{1.4}$	$23 \times \left(\frac{h_i}{20}\right)^{1.1} \leq \frac{h_i}{\beta_0}$
Stone wool insulation with $\rho \geq 26$ kg/m^3	0	$0.3 \times h_i^{(0.75 \times \log(\rho_1) - \rho_i/400}$
Glass wool insulation with $\rho \geq 15$ kg/m^3	0	for $h_i < 40\ mm$: 0 for $h_i \geq 40\ mm$: $(0.0007 \times \rho_i + 0.046) \times h_i + 13 \leq 30$

When using this approach with regards to CLT, the fire behaviour of the CLT is influenced by the adhesive used for bonding the panels. If the gaps between planks in lamella and gaps between lamella are less than 2 mm wide and the char layer does not fall-off when the char front has reached the bonded lamella, the separation function of the CLT can be calculated as that of a solid timber panel. However, if the char layer is expected to fall off then an increased char rate is expected on the surface now subjected to the fire and for simplicity the separation function can be calculated considering the single layers of the CLT panels. This represents the more onerous design technique as it gives lower fire protection values when adopting the improved method.

The position coefficients in the improved method are included on the assumption that the layers not originally exposed to the fire will have lower fire resistances than observed in testing or modelling i.e. if two boards in a build-up are of the same material and thickness, the protection provided by the external board will be longer than that of the internal board. This is because all layers of the assembly will begin at the same temperature. However, layers not originally exposed to the fire will be preheated by the time the preceding boards have failed. This leads to lower protection times than obtained in the tests of the isolated boards as no preheating effects are present.

Joint coefficients are included to consider the influence of different types of joints in protective boards not backed by battens, structural members or other boards. Joint types include butt joints, lap joints, finger joints, etc. The gaps in the joints are assumed not to be greater than 2 mm in compliance with EN 1995-1-2 as experiments found that the influence of joints with widths less than 2 mm and backed by a layer were minimal. In the context of this work, the layer could be the CLT panel, non-combustible blanket or another protective board.

7 Gap analysis

Areas identified for further research include

- The effect of where edges are glued during the manufacture of CLT on its fire resistance.
- The effect of fire retardants when used as part of the build-up, whether they are associated with the CLT and/or the protective lining;
- The impact of different methods for fixing protective boards to CLT, i.e. screwing, nailing or gluing, should be examined and the appropriate application method for each.
- Few fire-tested service penetration solutions exist for cables, pipes and ducts within CLT walls and floors through protected CLT build-ups however more are needed and in particular tests when these are used in conjunction with protective boards and other passive protection methods.
- Intersections between CLT walls and floors are noted as areas of increased charring however there are gaps in the current testing documentation for these intersections.

Ongoing research, including work associated with this report, aim to improve prediction techniques or models of compartment fires involving exposed CLT in which delamination of CLT or fall-off of protective boards may occur. These models require further attention and validation. Within intumescent coatings, further investigation into transparent intumescent and nano-intumescent research for wood substrates is desirable to determine the usability of these technologies with CLT.

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