# Compartment Fire Dynamics in Taller Timber Buildings: Guidance for Performance-Based Fire Safety Engineering

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**Abstract.** In comparison to non-combustible construction materials commonly used for taller buildings, timber elements can significantly alter the fire dynamics in a compartment. This fundamentally challenges many of the conventional fire safety strategies and design approaches for mid-rise and high-rise buildings. Consequently, many building industry practitioners are questioning the limitations of existing methodologies, while searching for additional ways to account for this different fire behaviour in the design, construction, and operation of timber buildings. In seeking to address these questions, this chapter describes the state-of-the-art and recent advances in understanding the fire behaviour in compartments with areas of exposed timber (e.g., engineered wood products), and protected timber elements that may contribute to the fire if their encapsulation fails. Relevant experimental findings and engineering approaches to date are summarised and discussed, and design guidance is provided in relation to the typical phases of realistic or 'natural' fires, namely the growth phase, the fully-developed phase, the fire decay, and the cooling phase. Critical fire phenomena and their impacts on the fire safety strategy are addressed, such as fire spread; active fire suppression; heat induced delamination and char fall-off; and self-extinguishment.

**Keywords:** Timber · Fire dynamics · Fire safety · Self-extinguishment · Heat induced delamination · Char fall-off

## 1 Introduction

Mid- and high-rise buildings present fundamentally different fire safety challenges than low-rise buildings due to the higher consequences of external flame spread, compartmentation failure, and potential collapse, as well as significantly longer egress times. These


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challenges have generally been addressed through prescriptive and/or performance-based design approaches that have been developed for buildings that are predominantly constructed from non-combustible materials (e.g., concrete, steel, masonry). In prescriptive approaches, an implicit level of safety is achieved for 'conventional' buildings by setting requirements that have been deemed adequate on the basis of years of experience and tradition. Examples of this include imposing restrictions on egress distances and mandating minimum separation distances between buildings. In contrast, performance-based fire engineering requires the explicit quantification of safety [1, 2]. This generally involves analysis of the fire dynamics in a building and the development of a fire safety strategy that quantifiably ensures that building occupants will not be exposed to untenable conditions, along with other objectives, such as preventing structural collapse or damage to neighbouring property. A holistic approach is critical in both prescriptive and performance-based design to prevent a single-point failure from invalidating the entire strategy for a building.

Understanding and reliably predicting the fire dynamics in a building is, therefore, fundamental to performance-based fire safety engineering. Over the past century, extensive research and development efforts have provided engineering tools that have become widespread and generally accepted for conventional buildings predominantly composed of non-combustible materials. As illustrated in Fig. 1, the timeline of a compartment fire can typically be divided into distinct phases that are addressed separately in fire safety strategies [3]. The initial 'growth phase' of the fire incorporates the period from ignition until a relatively steady peak fire size is reached—often following a rapid transition or 'flashover'. At the end of the growth phase, the fire enters the 'fully-developed phase', which generally continues until the available fuel has been consumed to an extent that the fire size begins to decrease. This initiates the 'decay phase', during which the fire continues to decrease in intensity until all the available fuel has been consumed. Finally, the 'cooling phase' incorporates the remaining time until the entire structure has returned to ambient temperature.

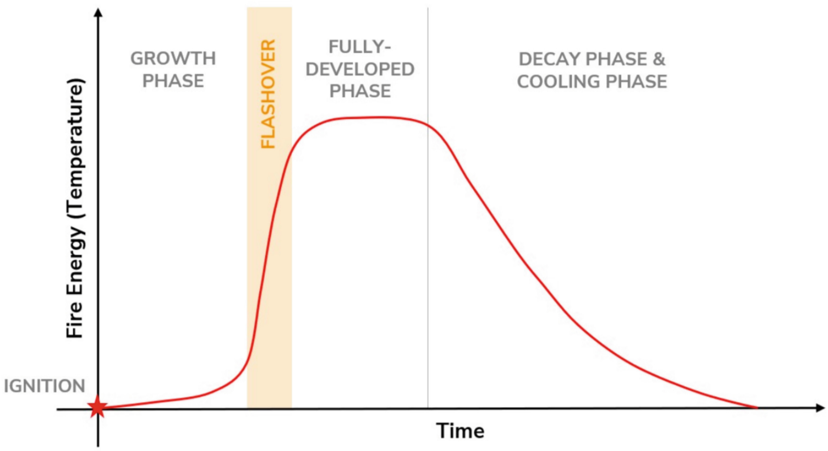


**Fig. 1.** Timeline of a typical compartment fire with distinct phases.

Compared to a conventional building, the additional combustible surfaces in a building with exposed timber elements—or with initially protected timber surfaces that can become exposed during fire—can drastically alter the compartment fire dynamics in every phase, to the extent that existing prescriptive and performance-based methodologies may not be applicable. This chapter describes the effects of timber elements on the compartment fire dynamics in each phase and provides guidance on how to account for this in performance-based design.

## 2 Growth Phase

After ignition, a compartment fire typically grows according to the available oxygen and the intrinsic fuel characteristics: physical and chemical properties, geometry, and distribution. This causes a gradual increment of the fire heat release rate (HRR [W]), which is typically approximated by an $\alpha \cdot t^2$ relationship in fire safety engineering applications ($\alpha$ [W/s$^2$] is the fuel-specific fire growth rate and $t$ [s] is the time from ignition). A smoke layer usually descends within the enclosure, compartment temperatures increase, and flashover conditions may be attained once the heat flux from the smoke layer is sufficient to ignite all combustible surfaces and items in the compartment. A core part of performance-based design related to this phase is to ensure that the Available Safe Egress Time (ASET) is greater than the Required Safe Egress Time (RSET)—the time necessary to allow for building occupants to reach a place of safety. The extent of the ASET is delimited by the time to onset of untenable conditions in the vicinity of occupants, due to unacceptably reduced visibility, exposure to smoke, and/or exposure to heat.

Recent research has highlighted that faster fire growth may be observed in timber-lined compartments. Flashover in exposed timber compartments has been observed to occur earlier than in non-combustible compartments [4, 5], exacerbated by the area, number, and configuration of exposed surfaces. Similarly, exposed timber ceilings in large open-plan compartments can promote faster fire spread rates and transition to fully-developed fire conditions once the combustible ceiling ignites [6–9]. The time to untenable conditions in a timber compartment can be shortened if timber becomes involved early in the fire, and this concerns the development of compartment temperatures [4, 10], smoke toxicity [11], and visibility. Consequently, the potential for accelerated fire growth in compartments with exposed timber can affect evacuation strategies and the design of active fire protection measures (e.g., smoke and heat extraction). To address these risks, it is crucial to account for ignition and flame spread over combustible timber surfaces and the energy contribution from burning timber. These challenges can be managed through encapsulation, timber treatments and well-maintained coatings, installing automatic suppression systems, or changing compartment geometries, for instance interrupting the continuity of a timber ceiling using beams or non-combustible elements. However, the impacts of these mitigation measures should be explicitly quantified to verify that an acceptable level of safety is still achieved, rather than relying on 'trade-offs' or comparative methods that may not account for the different fire dynamics in timber buildings.

## 2.1 Thermal Degradation and Ignition of Timber

Depending on the specific species, wood is generally composed of cellulose (40–55%), hemicellulose (15–35%), lignin (18–40%) and other minerals and extracts [12]. Like any construction material, wood is subjected to different thermal decomposition processes at elevated temperatures, which lead to both physical and chemical changes. As temperatures rise above ambient temperature, the moisture within the wood is displaced through diffusion and/or evaporation, until the wood is completely dried above 100 °C. For temperatures above 200 °C, wood typically starts decomposing (pyrolyzing) rapidly, releasing combustible gases and forming a residual carbonaceous char [13]. Above 300 °C, this char formation process is typically assumed to be complete, and the location of the 300 °C isotherm is commonly used to represent the base of the char layer as a simplified approximation for structural design. In the presence of oxygen, charred wood further degrades due to oxidation reactions (smouldering), typically initiated in the temperature range of 400–500 °C, until the char itself has been consumed [14]. In addition to the combustion of flammable gases produced through pyrolysis, oxidation of the char layer also releases heat (exothermic reaction), particularly during the decay phase when oxygen can more easily reach the char layer (due to the reduction of combustible pyrolysis gases released from within the timber members) [15].

During the growth phase, the production of pyrolysis gases creates a risk of ignition and flame spread over exposed timber surfaces that can increase the growth rate of a compartment fire. A value of 12 $kW/m^2$ is commonly used for the critical heat flux for piloted ignition of timber [3, 13]. Designers may prevent or delay the time at which this threshold is breached through adequate separation of timber elements from heat sources by, for example, encapsulating walls or increasing the height of an exposed timber ceiling above combustibles on the floor. This can be verified through heat transfer and/or fluid dynamics models that can estimate the temperature and/or heat flux to the timber during the pre-flashover stage. However, flame spread is an extremely complex process, particularly for vertical surfaces or beneath ceilings, and there are currently no computational models that have been validated for these scenarios. Consequently, delaying or preventing ignition is a more robust solution, particularly as research suggests that flame spread over exposed timber ceilings can be extremely rapid and lead to almost immediate loss of tenable conditions in a compartment [7, 9].

## 2.2 Fire Retardancy and Fire Protection

In order to reduce the ignitability of timber and its contribution to the fire growth phase (reaction to fire), fire retardants represent a common solution to delay (or prevent) ignition, and reduce flame spread and the energy (heat) release by the timber combustion [14].

Over decades, many different types of fire retardants have been developed and extensively used. However, while many fire retardants have shown effective performance, they are currently challenged due to their toxicity, volatility and leaching problems. Concerns also arise around their long-term durability and their impact on other timber characteristics, such as moisture sensitivity, appearance, weathering resistance, strength and stiffness [16]. Moreover, since fire retardants have been mainly developed to reduce the timber ignitability and flame spread during the fire growth phase, they are typically effective for relatively mild fire conditions (e.g., 30 kW corner fire in the EN 13823 Single Burning Item test) and their effectiveness can considerably vary depending on the heating conditions. This is evident in the case of intumescent coatings—swelling char-forming coatings that react upon heating—whose fire protection effectiveness largely depends on many factors, such as fire exposure and substrate conditions [17, 18]. Therefore, for a performance-based design, it is important that the designer determines the actual performance of the chosen solution (e.g., critical heat flux for ignition), rather than relying on standard classification and implicit assessments.

The impact of timber elements in the growth phase can also be limited through the strategic use of different types of encapsulation, such as calcium silicate and gypsum plasterboards. While in many cases it is preferable to expose timber surfaces for their aesthetic qualities, encapsulation materials are often required in some areas for other reasons, such as acoustic performance. Encapsulation materials provide a physical barrier that insulates the timber, slowing down the rate of temperature rise at the timber surface and thereby delaying pyrolysis and ignition. The effectiveness of these systems in the growth phase depends on their detailing (e.g., thickness, fixation and joints) and placement, and it is often important to ensure that they are also robust enough to function through the severe exposures in the fully-developed phase (see Sect. 3.2).

### 2.3 Active Fire Suppression

Active fire suppression systems are often applied to mitigate the fire risk when designing buildings with high fuel loads, to protect property from fire damage, and to prevent structural failure. The logic behind the use of active suppression systems is that they can limit and possibly suppress the growth of the fire. If designed and functioning correctly, these systems may provide a means by which the relatively higher heat release rates in timber compartments can be avoided. However, very little experimentation has been conducted where these systems were functional and used in the context of timber compartments. For example, Zelinka et al. 2018 [19] showed that sprinklers, when properly operational, can suppress the fire in a timber compartment, while another test showed the ability of a water mist system to control the fire [20].

It is important to recognise and account for the fact that active suppression systems are not 100% reliable and may fail in part or whole. Non-activation or delayed activation may result in the fire growing beyond the ability of the system to control it. Indeed, this was shown to be the case in the recent experimental work by Bøe et al. 2024 [21] involving a compartment where, as part of the study, the sprinkler nozzles were intentionally turned off and an adjacent corridor where the sprinklers were activated. The fire grew to flashover in the compartment and extended into the corridor. The sprinklers in the corridor had no effect on the fire, and the upper parts of the corridor walls and the ceiling ignited, with flames spreading along the corridor. This reveals an additional vulnerability of active suppression systems: fire spread on ceilings and upper parts of walls may not be suppressed if ignited, and conventional suppression systems are not designed to suppress fires in compartments with combustible ceilings. It is therefore important for the designer to recognise these issues and explicitly account for the potential failure of the suppression system in the fire safety strategy.

## 3 Fully-Developed Phase

A fire may be defined as fully-developed once it reaches a relatively steady maximum size and intensity, where the heat release rate inside the compartment is constrained by either the availability of oxygen (ventilation-controlled fires) or by the availability and configuration of fuel (fuel-controlled fires) [22, 23]. The fully-developed phase is generally initiated by a flashover, when all the exposed combustible surfaces and items in the compartment are almost simultaneously ignited by the intense heat flux provided by the smoke layer. The combusting fuel can be separated into the 'moveable fuel' (furniture and other temporary contents) and the 'permanent fuel' (integral building elements, e.g. walls and ceilings). The high heat fluxes in a fully-developed compartment fire will heat up and damage protection materials and structural elements, so the severity and duration of this phase are crucial factors in determining the performance of the structure and compartmentation. In taller buildings, the fire safety strategy usually requires that the structure must not collapse. This is essential for the safety of occupants and firefighters, and to prevent damage to neighbouring buildings and impairment of public infrastructure. Accordingly, in a performance-based design, the designer must ensure that the structure will maintain sufficient integrity and stability throughout the fully-developed phase, as well as the subsequent decay and cooling phases. This is known as 'design for burnout' [24].

During this phase, the additional fuel load from burning timber elements will increase the total heat release rate of the fire [4, 10, 25–27], which depends on the amount of exposed timber, the compartment geometry, and available ventilation [28]. In ventilation-controlled compartment fires, the excess fuel will combust outside the compartment, having minimal impact on the rate of heat generation internally. In fuel-controlled compartment fires, ignition of wooden surfaces will increase the internal HRR, raising the temperatures and heat fluxes within the compartment [29] and resulting in faster fire spread and a larger fire size in general [6–8]. Timber compartment linings also have better insulative properties compared to concrete or masonry, resulting in relatively lower heat losses and potentially higher compartment temperatures [30].

In both ventilation-controlled and fuel-controlled fires, the configuration of exposed timber surfaces can also alter the internal flow fields, resulting in highly non-uniform temperatures or heat flux distributions [26, 31]. In particular, burning walls may create higher local heat fluxes and momentum-driven flows that can invalidate design assumptions of uniform conditions in a compartment [31]. This is particularly problematic for 'zone models' and parametric fire curves that are commonly used in design, because the assumption of uniform conditions is fundamental to these models. Furthermore, higher oxygen concentrations near the floor of a compartment can support enhanced combustion and oxidation of charred material in this region, leading to greater damage to elements locally. Consequently, these methods should not be applied to compartments with exposed timber without consideration of the potential and consequences of non-uniform conditions.

The duration of the fully-developed phase may also be extended significantly if self-extinguishment of exposed timber surfaces is not ensured. Char fall-off or heat induced delamination, failure of encapsulation, or excessive heat feedback may all result in continued burning until failure of the structure or compartmentation [27, 29, 32].

### 3.1 Exposed Wood—Heat Induced Delamination and Char Fall-Off

As engineered wood products (EWPs) are composites with multiple elements glued together, their structural response relies on sufficient composite action, meaning that the bonded elements (e.g., lamellae or veneers) behave as a single unit. Debonding is a general term used for any loss of composite action. In ambient conditions, this failure can occur in timber, as timber is a natural composite; in the adhesive bulk; and at the adhesive-timber interphase. When exposed to fire, EWPs usually experience debonding in either the timber or the adhesive-timber interphase (i.e., bond line). This debonding in fire conditions is further divided into two types of failure modes: (i) char fall-off and (ii) heat induced delamination (HID), as presented in Fig. 2. Char fall-off may appear in any part of the charred cross-section. Heat induced delamination—i.e., delamination, glue/bond line integrity failure (GLIF) [33], and premature char fall-off [34]—appears in the proximity of the bond line.

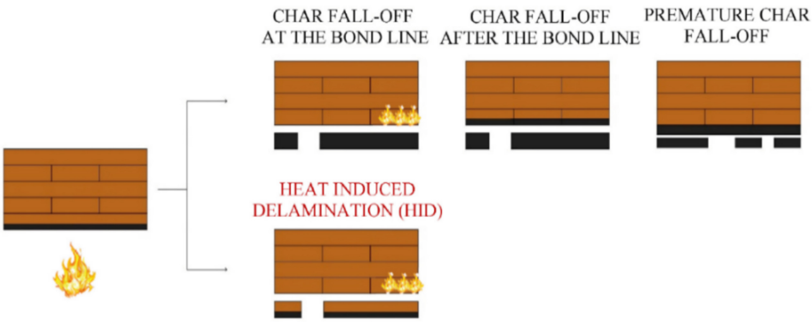


**Fig. 2.** Schematic representation of char fall-off and heat induced delamination from [38]. Reproduced under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Both failures initiate a change in fire dynamics and heat transfer [10, 27, 35, 36] because the loss of outer layers increases the heat transfer to the residual section (accelerating further degradation and pyrolysis), while the fallen pieces continue to combust and radiate heat back to the structural elements. This is particularly severe when burning pieces accumulate at the base of exposed timber walls, where oxygen concentrations are high, and the heat feedback can sustain flaming over the entire wall. The result is a cyclic phenomenon where the loss of the structural element's cross-section contributes to the ongoing burning of that same element.

In addition to the fire dynamics changes, HID may lead to the progressive loss of structural capacity [37] due to the loss of composite action and/or the premature loss of cross-section which has not completely charred.

When a large enough area is affected by HID or char fall-off, and the energy released by burning timber elements is sufficient, the compartment heat fluxes can be sufficient to sustain flaming combustion of the timber, even after the moveable fuel load is depleted. Similarly, if this occurs during the decay phase, a second flashover can occur. Both scenarios can extend the fire's duration and compromise the intended fire strategy, e.g., through failure of compartmentation or structural collapse.

Bond line response is dependent on the product (e.g. choice of adhesive chemistry, timber species, and manufacturing) and external conditions (e.g. heating conditions, orientation, mechanical stresses, and pressure induced by the moisture movement). To date, researchers have focused mostly on heating conditions, whereby the commonly accepted performance criterion is a generalised temperature. Thermal decomposition temperatures, such as glass transition, phase transition, or pyrolysis for adhesive and/or timber, can all compromise bond line mechanical response. In terms of the thermo-mechanical properties, both timber and adhesive film stiffness and strength start decreasing at temperatures lower than 100 °C [38, 39]. However, they do not deteriorate at the same rate, which can lead to unpredictable failure modes in both the timber and the bond line region [40, 41]. It was noted that HID can occur at bond line temperatures as low as 100 °C when the heating conditions are high enough to create a high moisture-related pressure gradient in the element and the load is sufficiently high [42]. However, the implications of mechanical stresses and moisture front position on the bond line response are still under research.

Current solutions for prediction and prevention of HID include careful manufacturing specification of the final product (i.e., thicker first lamella, edge bonding, and adhesive choice [25, 34, 37, 41, 43]). Designers are encouraged to impose a critical bond line temperature to account for HID depending on the adhesive and timber choice [38], at which the preceding lamella is considered as detached, and thus the layer is no longer accounted for thermally or structurally and is added to the fuel load.

### 3.2 Encapsulated Wood—Encapsulation Failure

Encapsulating some (if not all) timber elements is essential in higher consequence class buildings (e.g., buildings with vulnerable occupants, or where structural collapse would be too detrimental) because it directly impacts the life safety objective in the early stages of fire, as well as structural performance, compartmentation, and property protection during the fully-developed and decay phases.

For structures designed to survive burnout using encapsulation as a protection strategy, it must be demonstrated that the encapsulation will prevent the involvement of timber structural elements throughout the expected fire duration. This is relevant to both mass timber buildings and light-frame timber buildings. Designers should choose a challenging fire scenario, ignition threshold, and expected thermal and mechanical properties for the specific duration, and the integrity and insulation performance of the encapsulation should be quantified under those conditions. Additionally, to address the risk of continued smouldering after a fire, a management plan should be developed with the local fire service to remove the encapsulation in fire-affected compartments and check for hot-spots or other signs of combustion in gaps and concealed spaces [10, 44].

If the encapsulation fails due to loss of integrity (e.g., fall-off) or the wood behind exceeds the ignition threshold, the initially protected wood will begin to contribute additional fuel to the fire and mechanically degrade. This can extend the fire duration and lead to failure of the structure or compartmentation. Failure of encapsulation can occur due to insufficient thickness or fixing [45, 46], particularly if there is a higher fire load than the product was tested for (due to increased exposed timber surfaces and/or changes in fire dynamics) [47]. Due to the inherent uncertainties in encapsulation performance, safety factors and redundancies are essential.

### 3.3 Compartmentation Failure

Compartmentation is a fundamental aspect of the fire safety strategy, as it isolates the fire and stops it from spreading from its origin to other parts of the building (vertically or horizontally). This is crucial in taller buildings where fire spread (particularly vertically to other floors) may compromise many aspects of the overall strategy, such as egress, suppression, fire service intervention, and even the structural integrity. In a tall timber building with an inherently higher fuel load, the potential consequences of compartmentation failure are even greater.

#### 3.3.1 External Fire Spread—Exposure to Facades and Neighbouring Buildings

The additional fuel load from burning timber elements can lead to increased exposure to facades and nearby buildings or objects, especially in ventilation-controlled fires where the excess fuel combusts in an external spilled plume [26, 48, 49]. However, significant external flaming has also been observed in experiments with relatively well-ventilated timber compartments [9]. The flame height and thermal exposure to the facade are, among other things, dependent on the surface area of exposed timber, and the opening dimensions [48–50]. While models for predicting external flame height in exposed timber compartments have been proposed [49, 51], these have not yet been systematically validated in large-scale experiments, so they should be applied with a high degree of conservatism. Furthermore, many national standard façade fire tests do not induce the same level and duration of exposure as can be expected in severe fire scenarios [50].

Compounding the effects of greater external flaming in timber compartments, the exposure to neighbouring buildings will be even more challenging if the fire spreads to multiple floors. Currently, fires spreading externally from floor to floor on a building can be prevented by architectural constraints or fire-resistant glazing, which must account for the increased severity of external flaming due to exposed timber.

#### 3.3.2 Internal Fire Spread

The risk of internal fire spread may be increased if the elements contributing to compartmentation are not designed with consideration of the real fire exposure and duration in compartments with exposed timber. This includes the connections between elements, which generally require tolerance gaps and contain highly conductive metallic components. Furthermore, separating elements made from timber may promote the spread of fire or smoke through localised smouldering, or combustion of the timber in cavities between compartments. These risks can be reduced by preventing the timber separating elements from heating up significantly (e.g., by encapsulating them) and by avoiding or blocking cavities. Due to the persistent and highly localised nature of smouldering combustion [44], it may not be possible to entirely eliminate this risk through design. However, the relatively slow rate of smouldering combustion provides the opportunity for fire service intervention, and the fire service should be consulted and involved in developing a strategy to address this challenge. Overall, the robustness of design against internal fire spread can be improved through a multilayer approach to fire protection that avoids the potential for single-point failures.

## 4 Decay Phase

The fully-developed phase of a typical fire event lasts until the remaining fuel is no longer able to sustain the steady fuel- or ventilation-controlled heat release rate. This instant represents the beginning of the fire decay phase. During this phase, the conditions within the compartment evolve towards fuel burnout. As in the pre-flashover stages, the fire heat release rate is directly dependent on the fuel characteristics, and the compartment gas temperature tends to follow the fire heat release rate trend. The reduced soot production and increased intake of cold air through the opening results in a decrease in smoke density (increase in optical depth). The heat fluxes to the compartment elements significantly decrease, and the heat transfer becomes more complex and non-uniform [15].

While these phenomena are typical for traditional compartment fires with defined movable fuel load and non-combustible compartment elements, timber compartment elements can greatly affect the fire decay phase (i.e., onset, duration, etc.) [25, 35]. If flaming self-extinguishment of timber elements is achieved (see Sect. 4.1), the compartment will transition into the cooling phase. Conversely, under certain conditions, the combustible compartment elements can continue to burn and sustain the fire development, and timber compartments might never achieve flame extinction and burnout. Burnout of timber compartments is commonly considered to occur once the moveable fuel is consumed and flaming extinction of timber elements is achieved. This phenomenon is affected by many discussed factors, including the area and configuration of exposed timber, ventilation conditions, and compartment geometry [28, 32, 46].

### 4.1 Self-Extinguishment

During the decay phase, once the heat release rate from the remaining moveable fuel has decreased sufficiently, the incident heat flux on exposed timber surfaces may become low enough that the resulting pyrolysis rate of the timber can no longer sustain flaming combustion. Consequently, flaming on these surfaces will cease and their energy contribution to the compartment will reduce drastically (apart from residual smouldering). This process is known as flaming ‘self-extinguishment’ (also commonly known as ‘self-extinction’ or ‘auto-extinction’), although some use self-extinguishment to mean the end of both flaming and smouldering combustion [25]. Ensuring the conditions for flaming self-extinguishment of exposed timber surfaces is a crucial step in designing for the eventual burnout of a compartment fire.

Flaming self-extinguishment in timber compartments is a complex phenomenon that requires several conditions to occur [32, 46]. Fundamentally, the amount of heat from the compartment being transferred through the insulating char layer to the pyrolysing timber must fall below a critical value. Depending on the local oxygen concentration and airflow velocity, this can be achieved when the external heat flux onto the surface of the charring timber falls below 30–45 kW/m$^2$ [35, 52–54]. This critical heat flux criterion applies once the char layer has reached a sufficient thickness, so it can be invalidated by char fall-off or heat induced delamination that increases the heat transfer to the underlying timber [10, 35, 40].

Once the moveable fuel load has substantially been consumed, the residual thermal exposure to the exposed timber will be dominated by radiative and convective heat feedback from the other compartment surfaces. Consequently, the area and configuration of exposed timber surfaces must allow for the residual heat fluxes in the compartment to fall below the critical value. This also requires that the performance of encapsulation is maintained for protected timber elements, so that they do not contribute additional fuel and heat [10, 26, 27, 32].

Char fall-off or heat induced delamination and encapsulation failure all depend on the severity and duration of the fire. Therefore, controlling or accounting for the fuel load and ventilation characteristics in a compartment is equally as important as optimising the timber elements, adhesive, and encapsulation system (see Sects. 3.1 and 3.2).

In some cases, the configuration of exposed timber surfaces can have a greater influence on the potential for flaming self-extinguishment than the total exposed area, since this will control the heat transfer between surfaces. For example, the heat feedback between two or more adjacent burning timber surfaces may be enough to sustain flaming until the structure or compartmentation fail, or for long enough to induce encapsulation failure or delamination that subsequently causes a secondary flashover [10, 27, 32]. Furthermore, it may be safer to expose a ceiling than a wall, because the burning rate of the ceiling is often lower due to the lack of oxygen in the upper region of a compartment, and the optically thick smoke layer below the ceiling can reduce the radiation received from other surfaces [26]. As a limitation to this, it should be noted that most compartment fire experiments have not included mechanical loading of exposed horizontal elements, so they may not be representative of the effects of realistic stresses on the bond lines. Nonetheless, the total percentage of exposed area has been found to be strongly correlated to the incidence of self-extinguishment in compartment fire experiments, with a high occurrence of self-extinguishment for compartments with less than 20% of the total surface area exposed [28].

Considering the complexity and uncertainties involved in designing for self-extinguishment in timber buildings, it is essential to approach the design in a proportionately conservative way. As part of a holistic fire safety strategy, designing for self-extinguishment can reduce the risk of compartmentation failure and structural collapse. Nonetheless, the other elements of the strategy—e.g., providing safe egress routes and facilitating fire service intervention—should be robust and provide sufficient redundancy to avoid the possibility of cascading failures.

## 5 Cooling Phase

Once the movable fuel in a compartment has been combusted and flaming extinction has occurred on all the timber elements, the fire heat release rate tends to become negligible, and the compartment volume enters a pure cooling phase [15]. This phase is characterized by the two significantly different modes of cooling taking place in the gas-phase and the solid-phase. The smoke inside the compartment is rapidly evacuated and cold air flows continuously into the enclosure through openings. Consequently, the gases inside the compartment quickly become optically thin and tend to ambient temperature. In contrast, the solid compartment elements (e.g. linings and structural elements), slowly cool down through surface convective cooling, and radiative heat exchange occurs between the exposed solid surfaces. These cooling phenomena primarily depend on the characteristics of the compartment (e.g., geometry and opening) and its elements (e.g. thermal inertia of compartment elements), and they can be modelled using simplified numerical heat transfer models [55].

As regards timber structures, the relevance of considering the thermal conditions during the cooling phase has been highlighted by several researchers, particularly in light of the continuous wood degradation due to the in-depth penetration of the heat wave [15, 37, 55–59]. In addition, during this phase, timber compartment elements may suffer from significant smouldering, which typically acts over longer timescales but can eventually lead to failure of the structure or compartmentation without intervention [44, 59, 60].

## 6 Conclusions

Performance-based design of timber buildings requires explicit consideration of the realistic compartment fire dynamics and how timber elements can influence this. The combustible nature of timber has the potential to fundamentally alter the fire behaviour in comparison to a non-combustible building, and conventional design approaches are often incapable of accounting for this. By examining the current state-of-the-art research on timber compartment fire dynamics, the critical phenomena in each phase of a fire can be explicitly quantified and addressed in a holistic fire safety strategy.

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