We need to talk about timber

Citation for published version:
Law, A & Hadden, R 2020, 'We need to talk about timber: fire safety design in tall buildings', *The Structural Engineer*, no. 3. <https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-3/we-need-to-talk-about-timber-fire-safety-design-in/>

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
The Structural Engineer

We Need to Talk About Timber

Angus Law and Rory Hadden
School of Engineering, The University of Edinburgh

1. Introduction

The construction industry is characterised by ignorance, indifference, and lack of clarity on roles and responsibilities [1]. There is a culture across the sector which can be described as a '*race to the bottom*' [1]. There is insufficient focus on delivering the best quality building possible [1]. This, in May 2018, is how Dame Judith Hackitt described the UK construction industry – with her specific focus on buildings. Her interim report *Building a Safer Future*, was intended as 'a call to action for an entire industry' [2] – recognising that 'true and lasting change will require a universal shift in culture' [2].

The Westminster government's immediate response to Hackitt was to 'ban' combustible materials for use in the external wall of residential buildings with a height greater than 18 m [3]. The government's impact study in support of the 'ban' explicitly identified that the engineered timber industry would see significantly reduced growth due to post-Grenfell regulatory changes [4]. Has the use of a material that has been increasingly of interest to the tall building industry [5] suddenly been 'scuppered' [6]? Why was mass timber not included within the government's list of exemptions? It would surely have been easy to draft some text to exempt timber from the ban.

The proponents of tall timber have spent the best part of a decade talking down the combustible nature of timber. We are told that there is 'a common misconception about timber is that it is more susceptible to fire [than other materials]' [7]; that 'it's a very hard material to light' [8]; that it exhibits 'charring rather than going up in flame' [7]; and that 'it burns in a very predictable fashion' [9]. While there is some truth in these statements – the authors could make counter arguments: wood can be 'ignited relatively easily' [10]; 'mechanically, timber performs worse than steel or concrete at high temperature' [11]–[13]; in some cases exposed surfaces do 'not extinguish' [14]. In each case, the performance of timber construction depends entirely on the context.

It could perhaps be argued that simplistic messaging was necessary to overcome misconceptions, and to open the minds of non-specialists to the possibilities of mass timber construction in an industry which has been historically predisposed towards non-combustible forms of construction. A case in point is Bridport House, where a Registered Architect explained that 'we challenged [the residents] to set a big piece [of CLT] on fire. Which they duly tried and didn't succeed. From that point on [CLT] was accepted as the best way to make the main part of the building' [15]. For the same project, a contractor's site manager was quoted as saying 'cross-laminated timber is a massive timber material that does not bear extra risk in the case of fire. The outer parts would char, protecting the bulk of the material and bringing no danger of structural collapse' [16]. It could perhaps be assumed that behind the simplistic messaging, designers were – in fact – systematically identifying and addressing the new hazards.

If any further reminder could be needed about the importance of selecting appropriate construction materials, and adequately considering the hazards these materials present – Bridport House also serves as an unfortunate case study. It has recently been reported that the building must be 'emptied' [17] due the fire safety risks associated to the presence of combustible cladding. It was reported that the building's owner (Hackney Council) say that 'no tests were carried out to see if the insulation could be compliant with the cross-laminated timber frame and type of brickwork used at the block' [17]. Given this context, it is easy to imagine why the 'government doesn't trust industry' [18] and chose not to include mass timber within the list of exemptions to the 'ban'.

While visionary designers articulately and persuasively set-out why timber represents the future of the construction industry [19], [20] – it is our experience and observation based on multiple completed and proposed projects (and ongoing dialogue with designers, approval authorities, and enforcement agencies) that there is, and has been, a systematic failure to explicitly identify and address the hazards introduced by the use of engineered timber.

We have not been able to distinguish whether this failure is routed in ignorance, indifference, lack of clarity about roles and responsibilities, or is simply a symptom of Hackitt's 'race to the bottom'. Nevertheless, this paper, and the accompanying talk at the Institution of Structural Engineers [21] are an attempt to clearly articulate some of the key hazards associated with engineered timber – and show how these may be addressed by competent design professionals.

2. Common Building Situations

The current tallest timber building in the world stands at 18 storeys [22] and the 'world's largest CLT building' [23], Dalston Lane, is in the UK. These records are, however, unlikely to stand unchallenged for more than a year or two. Such structures are, by definition, ground-breaking – the first of their kind. As noted by Foster [24], 'definitions of "tallness" are subjective and dependent on context' – for fire safety we would suggest that tall timber buildings are those buildings where the fire strategy includes phased vertical evacuation, a stay put strategy, or where internal fire-fighting is required.

As designers push boundaries, it becomes increasingly important to explicitly check that the underlying assumptions of the engineering methods used remain valid. In England, the most common engineering tool that is applied to the fire safety design of buildings is the guidance of Approved Document B (ADB) [25]. This document is not a conventional design tool, in the way that a structural engineer might think about a finite element model or a structural Eurocode. Rather, Approved Document B provides a series of solutions that, if applied carefully and only where applicable, can allow the designer to meet the functional requirements of the Building Regulations. However, in precisely the same way as for any other engineering tool, the designer must carefully check that the assumptions that underpin the guidance of ADB (i.e. the design tool) remain appropriate for the given situation.

This idea is explicitly captured on the first page of ADB; the scope of application is *limited* in that the Approved Documents are intended to 'cover common building situations'. Where a building is the *tallest* or the *biggest* – it ceases, by definition, to be a common building situation. Such boasts draw explicit attention to the unusual nature of the buildings; wherever superlatives are applied in engineering, history has taught us to take particular care. Being the *biggest* would have brought little comfort to the passengers of the Titanic. However, it is not the superlatives themselves that require caution to be applied; rather, whether or not a step change that has occurred that means our previous insights and understanding no longer apply. It is therefore important that designers closely examine the assumptions that underpin the fire safety solutions presented in the guidance, to ensure they are applicable – and identify where they are not.

The 2019 version of Approved Document B is explicit that 'those with responsibility for meeting the requirements of the regulations will need to consider for themselves whether following the guidance in the approved documents is likely to meet those requirements in the particular circumstances of their case.'

2.1. The Safety Case and Professional Responsibility

A proposed building situation falling outside the scope of the guidance does not mean that the building cannot be built, or that it is likely to be inherently unsafe. In such cases designers must simply *demonstrate* the *safety case* [26] for their designs based on an explicit evaluation of the hazards – rather than a recourse to prescriptive guidance which is strictly applicable only to common building situations. Qualified architects are bound by the standard of professional conduct and practice, as defined by the Architects Registration Board. Similarly, structural engineers and fire engineers are bound by the professional codes of conduct of their respective institutions. For both architects and engineers, failure to demonstrate the safety case would be indicative of a lack of care in carrying out work. Similarly, claims of ignorance of the key issues would represent a failure to adequately maintain competence, and a failure to undertake work for which they are competent. The specific wordings associated to this *care* and *competence* are clearly stated within the relevant institutional codes of conduct [27]–[29]. The consequences of failing to make the *safety case* are therefore clear for each professional group.

Timber, unlike steel or concrete, burns. If a fire occurs in an engineered timber building, how does the hazard differ from a fire occurring in a steel or a concrete building? What happens during the fire? What happens after the fire has consumed the fuel in a compartment? Does the fire go out? Does the timber continue to burn until there is no structure remaining? To develop the safety case, the design professional must address these questions. The first step is to evaluate the hazards presented by the incorporation of timber into the building. Once the hazards have been identified methods can be developed to eliminate or mitigate them. Understanding the hazard presented by this material therefore starts with understanding how timber burns, and the conditions under which timber may stop burning.

3. Burning and Extinction of Timber

The burning of timber is well understood. The burning behaviour is captured by an extensive body of literature characterising characteristics such as critical heat flux, mass loss rate, and heat release rate, under a wide range of conditions [30]–[33]. It is understood that timber is a charring material and that, in the absence of an external heat flux, a thick timber element will be incapable of sustaining combustion. This is the principle of auto-extinction of timber.

Timber will contribute fuel to a fire when it begins to undergo pyrolysis. This is the process by which timber decomposes producing flammable gases and a rigid, carbon-rich char. In the presence of air, this char will be consumed by an oxidation reaction. The thermal decomposition is a function of temperature as illustrated in Figure 1(a) (for a piece of timber heated isothermally). Below 100°C, mass loss is attributed to drying of the timber. Between

200 and 350°C pyrolysis occurs which is characterised by rapid loss of mass. Above 350°C, char oxidation occurs.

With this knowledge, it is clear that below 200°C it is not possible for the timber to contribute fuel to the fire, as there will be no flammable pyrolysis gases produced.

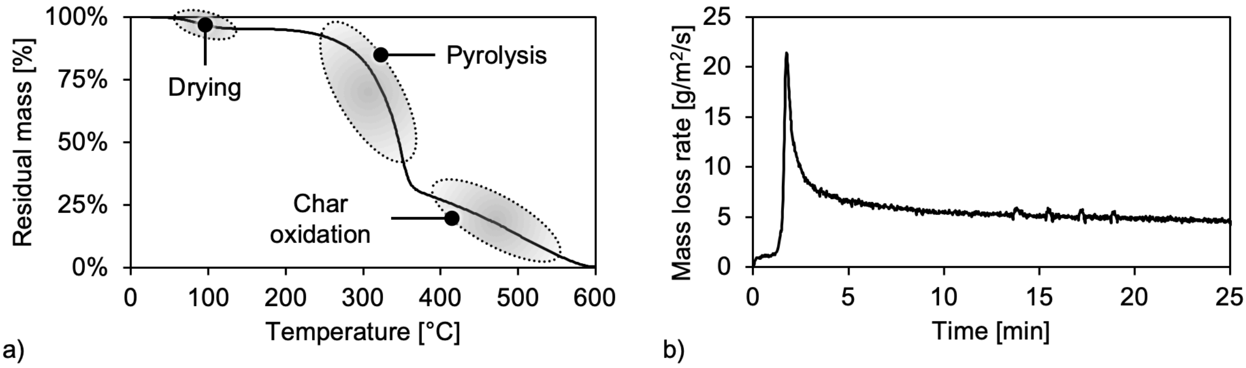

Figure 1 (a) Thermal decomposition of timber as a function of temperature (b) The burning rate of timber as a function of time when exposed to a heat flux of 40 kW/m^2.

The burning behaviour of timber exposed to a constant incident heat flux is shown in Figure 1(b). The burning of timber is a time dependent process characterised by an initial peak of high burning rate followed by a long decay in burning rate which may eventually lead to extinction of flaming combustion. This time-dependency is due to the formation of the char layer which reduces the rate of energy transfer to the pyrolysis zone and hence the pyrolysis rate.

Flaming combustion will only be sustained if the pyrolysis rate is sufficient to sustain a flammable gas-air mixture. The rate of pyrolysis per unit area (denoted by $\dot{m}_p''$) is driven by the energy received by the timber from any external heat sources ($\dot{q}_e''$), energy feedback from flame formed by the burning timber ($\dot{q}_f''$), radiative energy losses from the surface of the timber ($\dot{q}_{l,r}''$) and conductive heat loses into the timber ($\dot{q}_{l,c}''$) . Hence the pyrolysis rate is given by:

$$\dot{m}_p'' = \frac{\dot{q}_f'' + \dot{q}_e'' - (\dot{q}_{l,r}'' + \dot{q}_{l,c}'')}{\Delta H_p} \qquad (1)$$

where ΔH_p is the energy that must be supplied to drive the pyrolysis reaction. From this energy balance it follows that the energy gain ($\dot{q}_f'' + \dot{q}_e''$) must be larger than the energy losses ($\dot{q}_{l,r}'' + \dot{q}_{l,c}''$) for the pyrolysis reaction to occur. Small-scale experimental studies have shown that there is a critical mass loss rate ($\dot{m}_{p,crit}''$) of between 3.0 and 4.0 g/s/m^2 [34], [35] is required to sustain the combustion of timber.

Using the above formulation, it is possible to define critical values of $\dot{q}_e''$ for which burning of the timber will not be sustained and hence the timber will auto-extinguish. Using small-scale experiments, this value has been shown to be in the range of 30-45 kW/m^2 [36], [37] however there is little confirmation that this value is applicable under conditions relevant to compartment fires (e.g. at comparable orientations and length-scales).

4. Hazards and Mitigations

The fundamental hazard introduced by the use of engineered timber is that timber burns. However, the degree to which this results in other hazards is dependent on the overall fire safety strategy for a building and how the timber is used within the building.

In the case of tall buildings, it is typical that core components of the fire strategy will be an extended evacuation period (such as a phased evacuation in an office building); a ‘stay put’ strategy (in the case of residential buildings); and internal fire-fighting (using internal risers to supply water to upper floors).

Each of these strategies is predicated on the assumption that the stability of the structure will be maintained for an *indefinite* period of time. To achieve this, the assumption that underlies the guidance provided in Table B4 of ADB (and other similar codes and guidance used around the world) is that the prescribed periods of ‘fire resistance’ for tall buildings are sufficient to allow the structure to resist burn-out of the fuel load. This assumption dates back to the earliest work on ‘time equivalence’ by Ingberg [38]. It is clearly articulated some of the UK’s earliest design guidance (the Post War Building Studies’ Fire Grading of Buildings) that, based on a characterisation of a building’s fuel load, it was possible to formulate requirements grades of building that ‘should resist a complete burn-out without failure’ [39].

When the structural timber begins to burn, the fire dynamics in the compartment are affected. If the timber continues to burn then, it may consume all of the timber and failure will occur either in terms of loss of stability or breach of compartmentation. In a building where stability or compartmentation is required for life safety of occupants or fire service personnel, this is clearly not acceptable.

The hazards presented by the use of engineered timber are therefore as follows: 1) that the timber starts to burn; 2) that the timber continues to burn until there is no structure remaining; 3) that the additional energy released due to the burning timber affects the fire dynamics; and 4) the additional energy released due to the burning timber affects the spread of the fire from the compartment of origin. The safety case for a tall timber building must, therefore, explicitly address these hazards.

The challenge that structural timber poses to the idea of burnout, while not explicitly articulated in Approved Document B, was noted by the authors of the Post War Building Studies who identified that ‘all structural parts of [buildings that are required to resist burnout] should be of incombustible material’. In considering the historical underpinning of current guidance it therefore emerges that the presence of such hazards should not be considered as new, surprising or unexpected. They were identified, documented, and regulated more than 70 years ago.

4.1. Encapsulation

The simplest way to mitigate the hazards presented by timber is simply to prevent it from pyrolyzing. As described above, this can be achieved if the surface temperature of the timber does not exceed 200°C. This is a strategy known as encapsulation. If the timber can be prevented from burning, then there is a reasonable argument to be made that burnout can be achieved in a manner consistent with the assumptions underpinning Table B4 of ADB (i.e. there is no involvement of the combustible elements of construction). Hence, the minimum fire resistance periods presented in Table B4 could be applied without further consideration of how the combustible nature of the timber affects the overall fire safety strategy.

If this design approach is selected, then the encapsulation details must be able to prevent the engineered timber becoming involved in the fire for the duration of the required fire resistance period. To demonstrate that the protection system achieves this objective, any designer must undertake whatever verification methods *they* consider appropriate, and must then assume responsibility (and hence liability) for their design decisions. We would suggest that – at a minimum – appropriate fire testing should be undertaken on the detailing that will be used in the final application.

4.1.1. Partial Encapsulation

We have observed on several proposed and completed CLT building projects that designers have based their designs on an encapsulation strategy. However, in many cases, we have observed that encapsulation has been designed with an explicit assumption that the fire protection falls away from the timber at some stage *within* the specified fire resistance period – thereby exposing the surface of the CLT and allowing its subsequent involvement in the fire. This, to borrow from Buchanan [40], is more accurately defined as a *partial encapsulation* strategy; it does not prevent feedback between the structure and the fire, and does not achieve the objective of an encapsulation strategy as described above.

Those with responsibility for meeting the requirements of the regulations must recognise that if they assume the requirements have been met by a strategy of additive fire resistance alone (i.e. plasterboard protection time added to a time associated to the charring of the timber), they are failing to recognise that auto-extinction is a precondition for any strategy that includes burning of timber. For a building that incorporates phased evacuation, stay put, or internal fire-fighting – it cannot be assumed that a strategy of additive fire resistance will alone meet the requirements of the regulations.

There have been several examples of structural engineers explaining fire protection strategies for CLT buildings that fall precisely into these terms. For example in relation to Dalston Lane, a Chartered Structural Engineer at Ramboll was quoted in *Building* as saying 'the plasterboard gives 49 minutes of fire protection, after that the timber chars at 0.7 mm per minute so we have to ensure we have enough timber remaining to carry the loads after 120 mins' [41].

A case where there is some uncertainty about the degree to which timber encapsulation remained in place, even during project specific fire resistance testing, is TallWood House at Brock Commons. In previous correspondence in this magazine, Structural Engineers (PEng) at Fast + Epp when pressed to demonstrate that 'ignition of the timber did not occur within the two-hour fire resistance period' were 'not able to share the testing data' [42] and therefore apparently unable to confirm whether the charring visible in photos from their full scale test [43] occurred prior to, or after the end of, the specified fire resistance period.

In the event that encapsulation does not remain in place and prevent pyrolysis of the underlying timber, then the feedback between the fire and the structure has not been eliminated. Those with responsibility for meeting the requirements of the regulations must therefore either: reformulate their safety case to avoid phased evacuation, stay put, or internal fire-fighting (i.e. accept that structural failure of the building during a fire is a design assumption); or demonstrate that auto-extinction occurs.

4.2. Demonstrate Auto-Extinction

If the timber starts to pyrolise and burn, the key question that designers must answer is whether or not their compartment will auto-extinguish prior to loss of structural stability or loss of compartmentation. Once the imposed fuel load within the compartment (i.e. the furniture and other combustible contents) has been consumed, the timber will only stop burning if the pyrolysis rate of the timber drops below the critical value required to sustain flaming combustion.

Understanding and quantifying the feedback processes between the compartment fire and the burning timber require close examination of the energy balance for a compartment fire:

$$\dot{q}_C = \dot{q}_L + \dot{q}_W + \dot{q}_R \tag{2}$$

where $\dot{q}_C$ is the rate of heat release due to combustion, $\dot{q}_L$ is the rate of heat loss due to replacement of hot gases by cold, $\dot{q}_W$ is the rate of heat loss through the walls, ceiling and floor, $\dot{q}_R$ is the rate of heat loss by radiation through the openings. This neglects the rate of heat storage in the gas volume which is assumed to be small. In the case of a combustible compartment lining, the heat losses through the wall will include the energy required for pyrolysis ($\dot{q}_p$) as well as the transient conduction term ($\dot{q}_{cond}$) i.e. $\dot{q}_W = \dot{q}_p + \dot{q}_{cond}$. At the critical pyrolysis rate for auto-extinction, $\dot{q}_p = \dot{m}_{p,crit}\Delta H_p$ and, assuming that the imposed fuel load has burnt out, $\dot{q}_C = \dot{m}_{p,crit}\Delta H_{c,p}$ where $\Delta H_{c,p}$ is the heat of combustion of the pyrolysis products.

Making the substitutions, Equation 1 becomes:

$$\dot{m}_{p,crit}\Delta H_{c,p} = \dot{q}_L + \dot{m}_{p,crit}\Delta H_p + \dot{q}_{cond} + \dot{q}_R \tag{3}$$

and rearranging gives:

$$\dot{m}_{p,crit}\Delta H_{c,p} - \dot{m}_{p,crit}\Delta H_p = \dot{q}_L + \dot{q}_{cond} + \dot{q}_R \tag{4}$$

Recognising that $\dot{m}_{p,crit}\Delta H_{c,p} - \dot{m}_{p,crit}\Delta H_p = \dot{m}_{p,crit}\Delta H_c$ where ΔH_c is the heat of combustion of the timber, the energy balance at extinction becomes:

$$\dot{m}_{p,crit}\Delta H_c = \dot{q}_L + \dot{q}_R + \dot{q}_{cond} \tag{5}$$

For extinction of the timber to occur, the overall losses from the compartment must be greater than the energy generated due to the combustion of the timber. This can be expressed as follows:

$$\frac{\dot{m}_{p,crit}\Delta H_c}{\dot{q}_L + \dot{q}_R + \dot{q}_{cond}} < 1 \tag{6}$$

Identifying whether this criterion is satisfied requires either case-by-case testing of each compartment configuration to check whether auto-extinction occurs, or explicit evaluation of the parameters $\dot{m}_{p,crit}$, $\dot{q}_L$, $\dot{q}_R$, and $\dot{q}_{cond}$ at the time of burnout of the compartment fuel load.

The terms $\dot{m}_{p,crit}$, and $\dot{q}_{cond}$ will be determined by the material. However, it is noteworthy that the terms $\dot{q}_L$ and $\dot{q}_R$ are direct functions of the geometry of the compartment openings and therefore the ability to meet the auto-extinction requirement can be directly manipulated by decisions made at the design stage of the building. There is good reason to expect that, with adequate experimentation and with sufficient background knowledge, it will be possible to design compartments that consistently auto-extinguish. In this context it is worth considering that the fundamental fire science that controls the problem can, itself, become a means of generating designs; that is, architectural expression of timber defined based on fundamental physical laws. Just as the structural limitations of CLT limit the maximum spans that can economically be achieved, the flammability properties of the material will naturally suggest particular configurations of material and geometry of ventilation that are pre-disposed towards auto-extinction.

A key challenge in obtaining repeatable data to allow quantification of the terms of the energy equation is the delamination – sometimes referred to as 'char fall off' – of the timber lamellae during the later stages of a fire. Delamination increases the local heat release rate of the timber and can therefore significantly affect the energy balance; this introduces a stochastic variable that, to date, has been difficult to predict or quantify. This analysis also does not consider the effects of char oxidation or sustained smouldering combustion of the timber – the importance of this term with respect to the overall fire behaviour is as-yet relatively unknown.

4.3. Fire Spread

Once the likelihood of auto-extinction of a particular design configuration is established, other hazards can then be evaluated. Key amongst these is the potential for timber buildings to promote fire spread. Ensuring that building-to-building fire spread is adequately controlled is fundamental to the success of any form of urban construction, and is an issue that receives considerable attention within building regulations and statutory guidance. For tall buildings, vertical fire spread on the outside of a building (or floor-to-floor fire spread) is also a relevant consideration – particularly where an extended evacuation period, a 'stay put' strategy, or internal fire-fighting is required. Building-to-building and floor-to-floor fire spread are clearly, therefore, relevant considerations for tall timber.

External fire spread is driven by heat transfer outside the compartment. As described in the previous section, auto-extinction is more effectively achieved when the energy losses from a compartment are maximised. It is ironic that maximising these energy losses means that, by definition, more energy would be available to promote vertical fire spread and building-to-building fire spread – although the hazard presented by this may be somewhat mitigated by the distributed release of this energy through a larger opening.

For building-to-building fire spread, as with fire resistance, the guidance is underpinned by some fundamental assumptions [44]. These are: 1) that the internal linings of the building are non-combustible; and 2) the external fire plume can be ignored when considering building-to-building fire spread. By contrast, design consideration of vertical fire spread on the outside of a building is almost entirely dominated by the behaviour of the external fire plume.

Therefore, to address the hazards of fire spread, it is necessary to quantify the impact that combustible timber linings have on the (increased) radiation omitted from a compartment, and on the behaviour of the (more severe) external fire plume. Here we concentrate on the external fire plume.

4.3.1. Behaviour of the External Fire Plume

In compartment fires that are ventilation controlled there is insufficient supply of oxygen to allow all of the fuel (i.e. products of pyrolysis) to burn within the compartment. As a consequence, unburnt fuel can escape from the compartment (e.g. through the window openings) and burn in an external fire plume. In the case of compartments with timber linings, there is a larger exposed area of fuel – but no additional oxygen. It is logical, therefore, to expect more burning to occur externally.

The resulting larger extent of external burning has the potential to increase the heat flux on neighbouring buildings thereby increasing the likelihood of building-to-building fire spread; and also on the storey above the floor of fire origin – thereby increasing the hazard of breach of compartmentation. Higher heat fluxes can also be expected on the external cladding materials of the burning building itself – thereby increasing the likelihood of vertical fire spread.

The higher external burning rate and higher heat flux from the plume outside the compartment have been demonstrated to increase when timber linings are present. For example, recent work has measured incident heat fluxes that are three times greater on the facade above the opening when an exposed timber soffit is used in place of concrete [45].

We suggest that a key objective for designers should therefore be to identify the additional fuel that a CLT lined compartment may release, and the fire spread hazards that this presents. Only then can appropriate mitigation measures be identified and implemented.

5. Structural Stability

If a designer is successfully able to provide an assurance of burnout, either by encapsulation or by demonstrating burnout, there is a further structural challenge that must be overcome for tall timber buildings: ensuring that the structure remains stable and does not collapse after the fire has gone out. The decay phase of a fire is not typically explicitly considered within prescriptive design codes, and does not feature explicitly in ADB. However, there is good reason to pay greater attention to the decay phase in an engineering timber building than in an equivalent steel or concrete building.

Even after a fire has burnt out (or a fire testing furnace has been turned off), the temperatures deep with the core of a concrete or timber element will continue to rise. As a consequence, with any structure, there is always a possibility that the structure could lose stability after, rather than during, a fully developed fire. There have been relatively few cases where substantial failures have occurred on cooling [46] – which perhaps explains why, on the whole, designers have historically been able to avoid addressing this hazard.

The temperatures that are reached deep within the core of a structural element are typically much lower than those that are reached on its surface. As a consequence, it is likely that in a concrete element, the core will rarely exceed the 300-500°C required to induce significant structural damage to the material. However, timber is more vulnerable to ‘warm’ temperatures – losing between 50% and 65% of its strength by 100°C, and losing 100% of its strength and stiffness by 300°C. As a consequence, timber structures are more vulnerable during the decay phase of the fire.

Based on Eurocode 5 Part 2 calculation techniques it has been demonstrated that a glue laminated timber column that had ‘survived’ a 90 minute standard fire resistance test with 45% of its original crushing capacity retained less than 13% of its capacity 2-3 hours after the end of heating in the furnace [47].

We therefore suggest that designers should explicitly consider the propagation of the thermal wave during the decay phase of the fire, rather than simply relying on char depth calculations *during* the fire as is currently typical in design. This will ensure that a structure retains adequate stability during the decay phase of a fully developed fire. Design tools to perform these calculations are already available in current Eurocodes [13].

6. Conclusions

Architects or principal designers should be supported by engineering specialists who can adequately oversee and help to solve the significant engineering challenges presented by this form of construction. The first step in solving these challenges is to think freely about the hazards, and not to be constrained by existing paradigms of fire safety design. Creating a *safety case* for such buildings is only possible if designers directly address the relevant hazards using knowledge based on sound scientific evidence.

For buildings that require structural stability in order to support phased evacuation, stay put, or fire-fighting operations, the hazards presented by the use of engineered timber are as follows:

1. that the timber starts to burn;
2. that the timber continues to burn until there is no structure remaining;
3. that the additional energy released due to the burning timber affects the fire dynamics; and
4. the additional energy released due to the burning timber affects the spread of the fire from the compartment of origin.

Unless these hazards are addressed, tall timber buildings represent a step change that means many of our previous insights and understanding no longer apply; in such circumstances there is every reason to think that tall timber buildings fall outside the scope of Approved Document B. Designers must acknowledge the feedback loop between the structure and the fire dynamics, and either eliminate it by encapsulation or satisfy themselves that auto-extinction will occur. The physics that control the fire dynamics of auto-extinction have been outlined in the paper – and the stochastic problems of delamination and sustained smouldering combustion must be understood and properly accounted for during design.

With adequate underpinning experimentation, there is good reason to expect it will be possible to design compartments that will consistently auto-extinguish. Once this has been demonstrated, designers must address the hazard of external fire spread both vertically (from floor-to-floor), and horizontally (from building-to-building). Finally, designers must address the hazards during the decay phase to ensure that structural stability will be maintained until the structure returns to ambient temperature.

The evidence we have seen suggests that the hazards outlined in this paper have, in many cases, not been systematically addressed in the design of engineered timber buildings. It is our recommendation that if professionals who have been involved in the design or construction of engineered timber buildings (that are reliant on structural stability to support phased evacuation, stay put, or fire-fighting) should revisit their designs in light of the understanding presented in this paper.

Designers must not create a legacy of buildings where the hazards are not adequately addressed, with resulting negative implications for the safety of life, property protection, and property value. If such a legacy has been (or is being) created, then William J. LeMessurier provides an instructive example of how to proceed [48].

References

[1] Judith Hackitt, "Building a Safer Future Independent Review of Building Regulations and Fire Safety: Final Report", p. 5, London, 2018.

[2] Judith Hackitt, "Building a Safer Future Independent Review of Building Regulations and Fire Safety: Interim Report", p. 10, London, 2018.

[3] "Building (Amendment) Regulations 2018: Circular 02/2018."

[4] "Final Impact Assessment: Ban on combustible materials in external wall systems. Building (Amendment) Regulations 2018 SI 2018/1230", Ministry of Housing, Communities and Local Government, 2018.

[5] "Tall Timber: A Global Audit", CTBUH J., no. II, pp. 47–49, 2017.

[6] S. Cousins, "CLT keeps rising, but will Hackitt scupper it?", RIBA J., 2019.

[7] E. Heathcote, "Timber advocates reach for the skies", Financial Times, May-2017.

[8] G. White, "Dalston Lane: The World's Largest Timber Building", The B1M, 2017. [Online]. Available: https://youtu.be/YqGH1_tAjlU?t=142 . [Accessed: 30-Sep-2019].

[9] A. Thistleton, "Insight: Wooden Skyscrapers", TRT World, 2016. [Online]. Available: https://youtu.be/OrVycyu61Mk?t=596. [Accessed: 30-Sep-2019].

[10] D. Drysdale, An Introduction to Fire Dynamics, pp. 220, Third. Chichester: Wiley, 2011.

[11] EN1992-1-2, Eurocode 2: Design of Concrete Structures - Part 1-2: General rules - Structural fire design, vol. ENC EC2. 2004.

[12] EN1993-1-2, Eurocode 3: Design of Steel Structures - Part 1-2: General rules - Structural fire design. 2005.

[13] "BS EN 1995-1-2: Eurocode 5: Design of Timber Structures. General Structural fire design", 2004.

[14] S. Deeny, R. Hadden, B. Lane, and A. Lawrence, "Fire Safety Design of Modern Timber Buildings", Struct. Eng., vol. 1, no. 96, 2018.

[15] P. Karakusevic, "Living at Bridport House", Sotra Enso, 2012. [Online]. Available: https://youtu.be/ZUx94ER6joU?t=216. [Accessed: 30-Sep-2019].

[16] W. Probert, "Bridport House, London", 2013.

[17] L. Heath, "Council block in Hackney emptied due to 'potentially combustible insulation'", Inside Housing, Aug-2019.

[18] A. Law and N. Butterworth, "Prescription in English fire regulation: treatment, cure or placebo?", Proc. Inst. Civ. Eng. - Forensic Eng., (online in press) https://doi.org/10.1680/jfoen.19.00004.

[19] M. Green, "Why we should build wooden skyscrapers", TED2013, 2013. [Online]. Available: http://www.ted.com/talks/michael_green_why_we_should_build_wooden_skyscraper

s. [Accessed: 14-Nov-2019].
[20] A. Thistleton, “Architecture is political; it’s time for the timber revolution”, The Architects’ Journal, 2018. [Online]. Available: https://www.architectsjournal.co.uk/opinion/architecture-is-political-its-time-for-the-timber-revolution/10037547.article. [Accessed: 21-Mar-2019].
[21] A. Law, “We need to talk about timber”, 2019. [Online]. Available: https://youtu.be/rND9M-kmVX8. [Accessed: 30-Sep-2019].
[22] “CTBUH Ratifies ‘World’s Tallest Timber Building’ Following Height Criteria Update”, CTBUH, 2019. [Online]. Available: http://www.ctbuh.org/news/mjostarnet-tallest-timber-building/. [Accessed: 05-Jul-2019].
[23] “100 Projects UK CLT”, Waugh Thistleton Architects, 2018.
[24] Robert Foster, Michael Ramage, and T. Reynolds, “Rethinking CTBUH Height Criteria In the Context of Tall Timber”, CTBUH J., no. 4, pp. 28–33, 2017.
[25] Approved Document B - Volume 1: Dwellings. HM Government, 2019.
[26] Judith Hackitt, “Building a Safer Future Independent Review of Building Regulations and Fire Safety: Final Report”, pp 38, London, 2018.
[27] “The Architects Code: Standards of Professional Conduct and Practice”, Architects Registration Board, 2017.
[28] “Code of conduct and guidance notes, The Institution of Structural Engineers”, The Institution of Structural Engineers, 2019.
[29] IFE Code of Conduct. Institution of Fire Engineers, 2018.
[30] R. H. White and M. A. Dietenberger, “Wood Products: Thermal Degradation and Fire”, In: K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Ilschner, E. J. Kramer, S. Mahajan, and P. B. T.-E. of M. S. and T. Veyssière, (eds). Oxford: Elsevier, 2001, pp. 9712–9716.
[31] C. Di Blasi, C. Branca, A. Santoro, and E. Gonzalez Hernandez, “Pyrolytic behavior and products of some wood varieties”, Combust. Flame, vol. 124, no. 1, pp. 165–177, 2001, https://doi.org/10.1016/S0010-2180(00)00191-7.
[32] A. I. Bartlett, R. M. Hadden, and L. A. Bisby, “A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction”, Fire Technol., vol. 55, no. 1, pp. 1–49, 2019, https://doi.org/10.1007/s10694-018-0787-y.
[33] L. A. Lowden and T. R. Hull, “Flammability behaviour of wood and a review of the methods for its reduction”, Fire Sci. Rev., vol. 2, no. 1, p. 4, Sep. 2013, https://doi.org/10.1186/2193-0414-2-4.
[34] A. Bartlett, R. Hadden, L. Bisby, and B. Lane, “Auto-Extinction of Engineered Timber as a Design Methodology”, in Wold Conference on Timber Engineering, 2016.
[35] R. Emberley, A. Inghelbrecht, Z. Yu, and J. L. Torero, “Self-extinction of timber”, Proc. Combust. Inst., http://dx.doi.org/10.1016/j.proci.2016.07.077.
[36] A. I. Bartlett et al., “Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces”, Fire Saf. J., vol. 91, 2017, https://doi.org/10.1016/j.firesaf.2017.03.050.
[37] R. Emberley et al., “Description of Small and Large Scale Cross Laminated Timber Fire Tests”, in 12th International Symposium on Fire Safety Science, 2017, https://doi.org/10.1016/j.firesaf.2017.03.024.
[38] S. H. Ingberg, “Tests of the Severity of Building Fires”, Natl. Fire Prot. Assoc. Q., vol. 22, no. 1, pp. 43–46, 1928.
[39] “Paragraph 55, Fire Grading of Buildings, Part I”, in Post-War Building Studies No. 20, H M Stationary Office, 1946.
[40] A. H. Buchanan, “Fire Resistance of Multistorey Timber Buildings”, In: Harada K., Matsuyama K., Himoto K., Nakamura Y., Wakatsuki K. (eds), Fire Science and

Technology 2015, Springer, Singapore, 2017, pp. 9–16, https://doi.org/10.1007/978-981-10-0376-9_2.
[41] A. Pearson, “Dalston Lane: Tall Timber”, Building, 2016. [Online]. Available: https://www.building.co.uk/technical-case-studies/dalston-lane-tall-timber/5079749.article. [Accessed: 14-Nov-2018].
[42] “Verulam - Fire resistance at the TallWood House, Vancouver”, Struct. Eng., vol. 97, no. 4, p. 38, 2019.
[43] P. Fast and R. Jackson, “Comment & reply The TallWood House at Brock Commons, Vancouver”, Struct. Eng., vol. 97, no. 1, p. 39, 2019.
[44] M. Law, “Heat radiation from fires and building separation”, Fire Res. Tech. Pap. No. 5, 1963.
[45] A. Bartlett et al., “Heat fluxes to a façade resulting from compartment fires with combustible and non-combustible ceilings”, in 3rd international symposium for Fire Safety of Façades, 2019.
[46] T. Gernay, “Fire resistance and burnout resistance of reinforced concrete columns”, Fire Saf. J., vol. 104, pp. 67–78, 2019, https://doi.org/10.1016/j.firesaf.2019.01.007.
[47] F. Wiesner et al., “Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces”, Eng. Struct., vol. 179, pp. 284–295, 2019, https://doi.org/10.1016/j.engstruct.2018.10.084.
[48] Henry Petroski, To Forgive Design. p. 41, Cambridge, Massachusetts: Belknap Harvard, 2012.