NEEDS FOR TOTAL FIRE ENGINEERING OF MASS TIMBER BUILDINGS

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Alastair Bartlett[1], Felix Wiesner[1], Rory Hadden[1], Luke Bisby[1], Barbara Lane[2], Andrew Lawrence[2], Pedro Palma[3], Andrea Frangi[3]

ABSTRACT: Fire safety is widely perceived as a barrier to implementation of tall timber buildings, particularly for engineered mass timber buildings with significant areas of exposed timber and timber structural framing. This negative perception is exacerbated by a lack of scientific data or experimental evidence on a range of potentially important issues that must be properly understood to undertake rational, performance-based engineering design of such structures. With the goal of delivering fully engineered structural fire designs, this paper presents and discusses a framework for using scientific knowledge, along with fire engineering tools and methods, to enable the design of timber buildings such that, when subject to real fire loads, their performance is quantified. The steps in this framework are discussed with reference to the available literature, in an effort to highlight areas where additional knowledge and tools are needed.

KEYWORDS: Fire safety, design, timber, total fire engineering, tall buildings.

1 INTRODUCTION

Despite advances in the development of engineered timber, fire safety continues to be a key barrier to a full timber building renaissance, particularly for tall buildings with significant areas of exposed timber elements. This negative perception is exacerbated by a lack of high quality data and experimental evidence on a range of potentially important issues required to undertake engineering design. To deliver more advanced fire safe and adaptable solutions, a detailed design methodology based on the fundamental combustion and structural behaviour of timber, the resulting fire dynamics, and care in detailing and quality assurance during design and construction, are needed.

A framework for using fire science and engineering tools and methods to enable the performance of timber buildings subject to real fire loads to be determined and properly engineered is presented herein. The steps in this framework are discussed, with reference to the available literature, so as to highlight areas where additional research and development are needed. The goal is to review the literature in the most critical areas, and to highlight research needs rather than to critique available design methods; these have proved adequate in meeting architectural ambitions to date. However, the complexities of reality and the limits of the available knowledge and methods are openly discussed.

2 EXISTING METHODOLOGY

Conventional design approaches for high-rise construction typically rely upon the assumption of a non-combustible structural frame. Structural fire design guidance for high-rise buildings has evolved over many decades, within an engineering framework that effectively prevented timber buildings above a given height (specific limits depend on local regulations, although typically in the range of 4-6 storeys). With the advent of performance based regulation globally, and concurrent with advances in engineered timber construction technology and sustainability drivers in the construction sector, the traditional limits on the height and size of timber buildings have been steadily decreasing, and ambitious projects for high-rise timber buildings are becoming ever more widespread [1]. This paper focuses on mass timber elements consisting of either cross laminated timber (CLT) or glued laminated timber (glulam), since these are the materials most likely to be used in structural frames of high-rise timber buildings of the future. The discussion is relevant also for steel-timber or concrete-timber composite systems.

Current design codes [2] provide guidance on charring rates and changes in mechanical properties that can be used to perform structural fire resistance calculations for engineered timber elements. These are applicable only to ISO 834 [3] (or equivalent) fire exposures – and in most cases are at least partly based on computational models calibrated/validated using a comparatively small number of furnace tests on isolated structural elements under standard fire exposures [4]. The available codes and guidance therefore cannot be directly applied to real fires, or even to non-standard design fire scenarios. There is also a relevant question as to whether standard 'cellulosic' fire testing scenarios are representative of the fires to be expected in mass timber buildings [5, 6], and whether a more detailed examination of the fire dynamics in such buildings is warranted, particularly in cases where large areas of exposed timber are expressed.

[1] University of Edinburgh, luke.bisby@ed.ac.uk
[2] Arup, UK, barbara.lane@arup.com
[3] ETH Zürich, frangi@ibk.baug.ethz.ch

The available methods are presently unable to account for or predict a range of potentially important phenomena: (1) delamination (i.e. surface ablation, or so-called 'loss of stickability' of fire-exposed lamella) – a phenomenon by which the outer lamellae, or parts thereof, of an engineered timber product detach during fire; (2) possible changes in compartment fire dynamics due to the effectively increased fire load and changes in distribution; or (3) continued flaming (or smouldering) of the timber construction after burnout of the compartment contents – all of which may be important considerations in compartments with exposed timber.

A worst-case design scenario for tall buildings (i.e. if the fire brigade are unable or unwilling to extinguish a fire) requires that a building survive burnout of its internal contents without intervention. Many in the building industry appear unaware of this fundamental intent, which forms the basis of structural fire resistance design. A design for burnout mind set is particularly important when considering the structural fire performance of tall timber buildings to prevent uncontrollable fires and to protect life, property, business continuity, etc.

3 PROPOSED METHODOLOGY

To address the specific risks associated with fires in tall timber buildings, explicit consideration of features unique to combustible construction in fire is required during design, construction, and use. The concept of 'total fire engineering' [7] can be applied during design to show how structural fire safety engineering design should be approached across all such projects. The design stages of an existing Total Fire Engineering methodology for non-combustible construction, proposed by the authors for designing timber buildings with exposed timber elements, are given in Table 1.

Table 1: *Concept Steps for Total Fire Engineering Design* [7]

(1)	Define and agree the structural fire performance objectives
(2)	Develop relevant design fire(s) and resultant fire dynamics
(3)	Idealise fire exposure as heat flux condition at boundary of construction (i.e. surfaces of the structural elements)
(4)	Conduct heat transfer analysis to determine thermal propagation and thus temperatures throughout construction
(5)	Determine thermal and mechanical material response at elevated temperature, possibly including: loss of material (charring, spalling, etc.); stress/strain response; thermal expansion, deformations, thermal loads, etc.
(6)	Determine resultant structural response and assess against pre-defined acceptance criteria, realistic structural interactions and critical failure modes
(7)	Mitigate uncertainty through confidence, sensitivity analysis, and/or risk assessment
(8)	Take design actions, providing requisite levels of performance subject to agreed functional design objectives

Each of the steps in Table 1 is equally applicable to combustible construction; however, to account for the additional aforementioned phenomena, at least two key modifications to the process are necessary. First, development of the design fire and the resultant fire dynamics in Step (2) must account for the effects of the exposed combustible construction and the thermal properties of the compartment boundaries. Second, an additional step (between steps (5) and (6)) is needed to evaluate whether the enclosure can survive burnout of the contents, and whether the construction can auto-extinguish (i.e. stop burning after the compartment contents are consumed). Furthermore, it is important to consider the greater interdependency between the steps that may be important for combustible construction. For instance, the presence of large areas of exposed timber may lead to a longer or more severe fire, smouldering combustion may play an important role, or delamination of outer timber lamella may result in secondary flashover or other changes to the compartment fire dynamics, etc.

4 STATE-OF-THE-ART

The aim of the current paper is to discuss the key areas in which additional research/knowledge is needed to support application of an engineering design framework similar to that given in Table 1. A number of knowledge gaps, in six strongly interdependent categories, prevent full application of this methodology to timber buildings: (1) pyrolysis and charring; (2) fire dynamics; (3) delamination; (4) smouldering; (5) thermo-mechanical properties; and (6) real structural response. In some areas a great deal of relevant information is already available, and it is simply a matter of raising awareness of the available knowledge; in other areas little is known and additional original research is required.

4.1 PYROLYSIS AND CHARRING

When exposed to heat, timber undergoes various physical and chemical changes, depending on the magnitude and duration of heating and the thermal boundary conditions, arising from a combination of dehydration, pyrolysis, flaming combustion, and smouldering combustion; all of which depend on complex, coupled material and system properties.

The rate of charring of timber has become the fundamental parameter of interest in structural fire resistance design of timber, and standardised charring rates are widely used in design to estimate the size of the 'residual' cross section assumed to remain structurally effective after a specified duration of exposure to the standard fire, such that the element's load bearing capacity can be approximated and compared against the load demand during fire. The majority of experimental campaigns exploring timber pyrolysis and charring have done so by studying charring rates; typically defined as the rate at which the char front propagates through a sample. This is often reported as the final char position divided by the test duration, or in some cases by monitoring the position of the 300°C isotherm. The charring rate in reality may be highly variable.

4.1.1 Effect of Material Properties

Charring rate is commonly acknowledged to be dependent on density [8-10], with various charring models [11-13] using density as a key input variable. However, for simplicity, the influence of density is usually not considered for the fire design. In general, it has been found that charring rates under exposure to the standard temperature-time curve [3] vary from about

0.8mm/min for some light, dry softwoods to about 0.4 mm/min for some dense, high moisture content hardwoods. Decreasing density results in reducing thermal conductivity which will also result in increased flame spread rates for lower density timber [13].

The presence of moisture is also widely acknowledged as retarding pyrolysis [9, 12, 14]. Friquin [9] reports that moisture content has a significant effect, with charring rate decreasing with increasing moisture content, as more energy is required to evaporate the water. However, it is difficult to make quantitative statements regarding the influence of moisture on charring in real fires based on the data available in the literature. In any case most timber in buildings will be at an equilibrium moisture content in the range of 9-12% [15], and is it unlikely that its influence will be substantial in practice.

The permeability of timber is known to affect its pyrolysis behaviour, with increasing charring rate as permeability increases [9, 16]. This is largely associated with grain direction, since permeability along the grain is up to four orders of magnitude higher than across the grain [9, 16]. Small changes in grain angle can thus result in large changes in moisture and oxygen transport, and significantly affect the charring rates [16]. Thermal conductivity is also greater parallel to the grain, thus also affecting charring [9]. White [17] tested various composite timber products and found that some tests showed faster charring perpendicular to the grain, although this was attributed to delamination and fissures.

Wood species [9, 13, 18] affects factors such as density, moisture content, and permeability. Additional factors specific to a species, such as chemical composition (e.g. lignin content [9, 19]) and anatomy [9, 12], may also influence pyrolysis and charring. However, the impact of species is not expected to be critical for softwood lumber used in engineered mass timber buildings.

4.1.2 Effect of System Properties and Test Method

Pyrolysis and charring of wood are affected by test samples' orientation, due to inevitable effects on fire dynamics and airflow over the sample [20]. However, contradictory results are given in the literature, and no firm conclusions on the specific effects can be drawn. The literature indicates that pyrolysis rates increase with sample size, although relatively few authors have investigated this effect [9, 21], and in real buildings the differences are probably negligible.

4.1.3 Effect of Fire Protection

The application of external fire protection is a well-known method of increasing the standard fire resistance of timber members [2, 22], when evaluated using furnace testing. Through a similar process, the presence of a robust, 'stickable' char layer in unprotected mass timber elements, once developed, will also act as effective protection for virgin wood below [8, 9, 23, 24]. As a result, the pyrolysis rate of unprotected, fire-exposed timber is initially high while no protective char layer exists before decreasing to a lower, quasi-constant value once a stable char layer has formed [23]. Schaffer suggests that a char depth in the range of 6 [13] to 12mm [25] is needed before a constant charring rate is reached.

It is also acknowledged that when a protective layer falls off – either insulation board or due to delamination of a timber lamella – the pyrolysis rate increases for a period of time (about 20 mins), before stabilising again [24]. The thickness of lamellae is thus important to the fire behaviour of CLT in cases where delamination occurs. If lamellae are sufficiently thick, then the charring response is effectively the same as for solid timber [26]. Otherwise variable/increased charring rates need to be assumed for design [23, 24].

4.1.4 Effect of Severity of Heating

The heating scenario is well known to significantly affect the charring rate of timber [10, 14, 20, 23, 27]. Increasing net heat fluxes result in increased pyrolysis and charring rates, with the rates approximately linearly dependent on net heat flux (however with considerable scatter based on the available literature). Inghelbrecht [28] has demonstrated that the mass loss rate (a proxy for charring rate) of softwood timber tends towards an asymptotic value regardless of heat flux, suggesting that it is only the initial (higher) charring rate that strongly depends on external heat flux. Charring rates under steady-state conditions (i.e. once a char layer has developed) may be less dependent on external heat flux than previously believed. Schaffer [13] notes that crack and fissure formation and size also depend on gas temperature, and this may also influence charring.

4.1.5 Charring Rates for Design

Despite the complexities discussed above, most standards assume constant charring rates on the order of 0.64mm/min for ISO fire exposure. This is based on an average value obtained from tests on several timber species in a variety of conditions [29] by the Joint Fire Research Organisation using standard fire tests on floors [18]. The New Zealand code [30] prescribes a charring rate of 0.65mm/min. The Eurocode 5 [2] specifies a one-dimensional charring rate of 0.65mm/min for softwood, regardless of density, which is also applicable to glued laminated timber. The same value is specified for hardwoods with densities below 290kg/m^3, however a reduced value of 0.50mm/min is given for hardwoods with densities above 450kg/m^3 and linear interpolation is used between these values. Eurocode 5 [2] also includes, for softwood beams or columns, a slightly higher notional charring rate of 0.7mm/min for glulam and 0.8mm/min for solid timber to account for the corner rounding that occurs during two-dimensional charring. As already discussed, initially protected timber is expected to char at a higher rate when protection (or char in the case of CLT) falls off [31]. The Australian standard [32] considers variable charring rates as a function of timber density, whereas in North America the AFPA [33] recommend decreasing charring rates with time of exposure to fire; this is likely to account for the initial peak in charring rate which is experienced before a stable char layer has formed.

Figure 1 shows the variation of charring rates with timber density from the available literature, for standard fire exposures in fire testing furnaces. Also shown are the charring rates suggested in various design codes. The variability in the available data is clear, and designers ought to keep this potential variability in mind when undertaking simplified structural fire engineering calculations based on notional charring rates. Finally, it is noteworthy that the NFPA Guide for Fire and Explosion Investigations [34] correctly states that different fire intensities yield different charring rates.

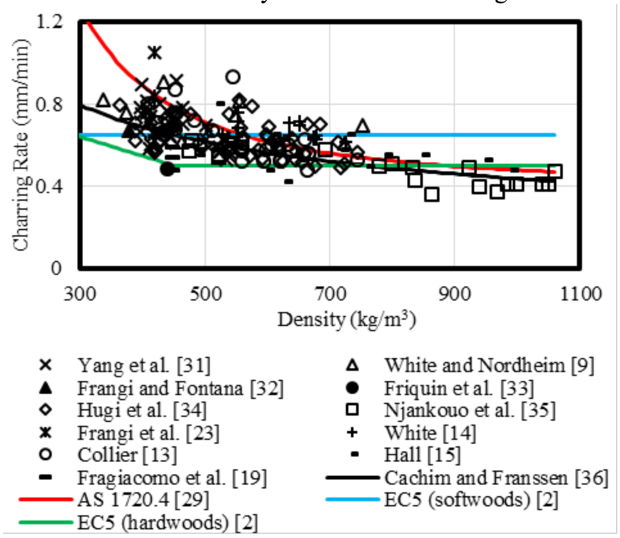

Figure 1: *Variation of charring rate with density*

4.2 FIRE DYNAMICS

Whilst some research is available on CLT compartment fires [6], considerable uncertainty remains regarding the extent to which the fire dynamics are affected due to varying amounts of exposed timber in real buildings. As noted previously in Section 2, a key criterion for design of tall mass timber buildings will be the occurrence of auto-extinction; and the conditions under which this can realistically be assured.

As with any building fire, an interaction exists between the fire and the compartment linings. This becomes more complex for flammable linings such as timber, since the walls, ceilings, and floors are susceptible to combustion that will produce additional pyrolysis gases, causing a coupling between the burning of the fuel and the burning of the compartment itself. Large solid timber panels (e.g. CLT) have a reduced risk of fire spread through void cavities as compared to light timber frames [41], but may increase the effective fire load due to the available surface area of timber and possible delamination during heating (Section 4.3) [42]. Additionally, external flaming from a compartment opening may be more severe, and this may have important effects on external cladding or façade systems, potentially increasing vertical fire spread or necessitating greater fire separation to protect neighbouring buildings.

A number of full-scale fire tests have been carried out on heavy timber or timber-lined compartments. Frangi and Fontana [43] undertook fire tests on modular timber rooms (6.6× 3.1× 2.8m high) with an opening factor of 0.041 $m^{0.5}$ to investigate the response times and efficiency of detection and sprinkler systems, as well as to study the structural response. Four different modules were tested; two had combustible oriented strand board (OSB) linings, and two were lined with gypsum board. Three compartments had timber board flooring, and one had a floor formed from hollow core elements. All floors were covered by linoleum. The total fire load density for rooms with non-combustible linings was 363-366MJ/m^2, whereas for rooms with combustible walls and ceilings it was 855MJ/m^2. Flashover occurred 30-55% earlier in modules with combustible linings, and external flaming was much more severe. No obvious differences were measured in compartment temperatures for combustible linings, due to limited availability of oxygen for additional combustion of unburned pyrolysis gases within the compartments.

Hakkarainen [44] carried out three tests on laminated timber rooms (4.5× 3.5× 2.5m) with an opening factor of 0.042$m^{0.5}$ and varying amounts of gypsum board protection (including an unprotected test). The total fire load was 720MJ/m^2 from wooden cribs. In the unprotected test the compartment temperature averaged about 700°C, which was 300°C to 500°C lower than predicted by a parametric fire analysis [45]. This was due to insufficient oxygen being available for complete combustion within the compartment, resulting in unburned gases flowing out the compartment and burning once in contact with sufficient oxygen [43]. Compartment temperatures increased towards the end of the test, although no clear explanation for this is given.

Frangi et al. [41] have presented a full scale test on a three storey CLT building. Since the CLT panels were fully encapsulated this test cannot be used for understanding the behaviour of compartments with exposed mass timber, although it highlights the well-known benefits of non-combustible encapsulation.

McGregor et al. [46] report five tests on CLT rooms (4.5× 3.5× 2.5m) with an opening factor of 0.042$m^{0.5}$. Two of these tests involved unprotected timber linings: one with propane used as a fuel source, and the other using furniture. In the unprotected tests the CLT panels became rapidly involved during the growth phase of the fire, resulting in an increased fire growth rate. Ceiling panels ignited first, and within 20s all exposed CLT surfaces ignited leading to rapid flashover. Combustion of exposed CLT surfaces contributed about 50% of the total 7MW HRR during the initial 20-30 minutes of burning, without any obvious delamination. This HRR contribution rose steadily to close to 100% of the 5.5 MW total HRR after 60 minutes, at which point the test was extinguished. Involvement of CLT surfaces had no noticeable effect on the gas temperatures inside the compartments, however CLT surface involvement in the fire increased the fire growth rates leading to reduced times to flashover and tenability times, as well as increased generation of volatiles and smoke. Localised delamination of the CLT was observed to momentarily increase the HRR due to burning of newly exposed timber and until a new char layer had been established.

Crielaard [5] presents a series of small scale tests on CLT compartments with various amounts of exposed timber surfaces, to study the self-extinguishment of CLT once the contents of a fire compartment have burned out. The full details of the study are avoided here, however it was shown that delamination of CLT lamellae during the cooling phase of a compartment fire can sustain flaming combustion, or lead to a transition from smouldering back to flaming combustion (i.e. secondary flashover). Crielaard [5] goes on to show that delamination of exposed CLT linings can be prevented by an increased thickness of the top lamella, such that the charring front does not reach the adhesive line.

Considerable additional research is needed before definitive conclusions on the fire dynamics in compartments with large areas of exposed timber can be stated with confidence. However, the available testing and above discussion suggest that fires in such compartments can be expected to exhibit:

- faster fire growth and reduced time to flashover;
- no increase in compartment gas temperatures, since oxygen availability governs the combustion process and heat release rate within the compartment;
- increased production of volatiles and smoke due to extra fire load for a given ventilation condition; resulting in increased severity of external flaming;
- increased *total* heat release rate (up to 100%); and
- the potential for secondary flashover, due to a combination of smouldering, delamination, and re-radiation within the compartment [5].

4.3 DELAMINATION *OR* 'LOSS OF STICKABILITY'

Delamination is a phenomenon where the outer lamellae, or parts thereof, detach from a timber element. It is a topic of particular importance because delamination may result in increased burning, due to generation of additional combustible surfaces during the fire, or to re-ignition of the newly exposed timber, causing changes in the fire dynamics and possibly leading to a 'secondary flashover', as well as accelerating the loss of cross-section due to pyrolysis and charring; thus accelerating reductions in load-bearing capacity.

It is thought that one of the primary causes of delamination is softening of the polymer adhesive(s) used in engineered timber manufacture, and several researchers have thus focused on this issue. However, a range of other factors may also influence delamination, including: the magnitude of applied loading, thermal deformations, dehydration, cracking and warping, lamella thickness, heating conditions, sample orientation, grain and lamella orientations, and mechanical restraint.

Schaffer [13] comments on the influence of adhesive type on delamination. Samples of glulam Douglas fir were subjected to heating in furnaces, in a vertical orientation, and it was found that lamellae bonded with phenol-resorcinol adhesive resisted delamination during fire. Frangi et al. [24] tested spruce CLT panels in a horizontal furnace under standard fire exposure. Specimens were bonded either with polyurethane (PU) or melamine urea formaldehyde (MUF) adhesives. The effective charring rates increased after delamination of the outer lamella for samples bonded with PU adhesive. Samples bonded with MUF adhesive did not delaminate, and thus the effective charring rates remained approximately constant. Frangi et al. [24] confirmed that using thicker lamellae resulted in lower effective charring rates due to less frequent delaminations.

Frangi et al. [26] have also presented furnace tests carried out on solid spruce panels and spruce CLT panels bonded with a PU adhesive, in both horizontal and vertical orientations. In a horizontal orientation delamination occurred between 26.5 and 28 minutes into the test, resulting in average effective charring rates about 30% greater than for equivalent solid timber panels. In a vertical orientation the effective charring rates were unaffected by delamination, whereas in a horizontal orientation the effective charring rate was 35% greater due to delamination.

Whilst the effects of delamination on effective charring rates during furnace tests are reasonably well understood, its causes and contributory factors (and the critical temperatures associated with failure) should be studied in greater detail, to allow its reliable prediction. In particular, the failure modes and influences of different adhesives require additional study.

4.4 SMOULDERING

A particular concern for high-rise mass timber buildings, as compared with steel or concrete buildings, is the potential for continuing smouldering once the compartment contents have burned out, either within the compartment or within concealed or encapsulated spaces adjacent to the fire compartment. Smouldering is a complex phenomenon in which the pyrolysis of the timber is driven by surface oxidation of the char. Smouldering is a flameless, heterogeneous mode of combustion, which is characterised by pyrolysis and oxidation of solid fuel and is typically slower and cooler than flaming combustion [47]. From temperatures of 300 to 600°C, oxygen can exothermically attack the exposed char layer [48], causing it to smoulder. This is most likely to occur after the burnout of the compartment contents, because the timescales required are much longer than for flaming combustion. Smouldering is not thought to be significant during the flaming stages of a fire because the flaming combustion consumes available oxygen before it can reach the char surface.

Solid phase char oxidation is the main heat source in smouldering combustion [47] and can lead to self-sustained smouldering if the oxidation rate is sufficient to drive the endothermic pyrolysis process [47]. Under certain conditions, transition to flaming combustion may occur, leading to sustained fire growth [47]. However, in the absence of external heat sources or effective insulation the heat losses from smouldering are typically too large to allow sustained smouldering for extended periods. Self sustaining smouldering of timber has been found to continue only when material is exposed to external heat fluxes of about 6-10kW/m^2 [5, 28]. During the cooling stages of a fire, the temperature within the wood will often rise above gas temperatures due to increasing char combustion after gas-phase combustion has ceased [49].

It is noteworthy that lower heat fluxes may allow for greater char oxidation in some cases, since volatile flow is low and oxygen is able to reach and react with the char [9]. For example, thermogravimetric analyses at different heating rates has found char to oxidise at temperatures raging from 400 to 650°C [50]. Also the yield of toxic species including carbon monoxide is higher during smouldering as compared with flaming combustion [50]. Propagation of smouldering is heavily dependent on the rate of oxygen flow to the reaction zone [47]. One-dimensional smouldering is an idealised scenario often approximated in real fires. This is characterised relative to the direction of the oxygen flow – with either forward or reverse propagation. Forward smouldering is characterised by propagation velocities on the order of 1mm/min, however reverse smouldering is much slower with propagation velocities on the order of 0.1mm/min.

Crielaard [5] tested twelve 100× 100× 50mm thick softwood CLT samples under a cone calorimeter at $75kW/m^2$. When the samples had achieved a char depth of 20mm they were moved to a second cone calorimeter at a heat flux between $0\text{-}10kW/m^2$ to determine the critical heat flux for extinction of smouldering; this was found to be $5\text{-}6kW/m^2$. Crielaard also performed experiments using forced airflows of 0.5 and 1.0m/s over smouldering samples, and found that whilst the 0.5m/s airflow led to faster extinction than with no airflow, forced airflow of 1.0m/s led to sustained burning at a heat flux of $6kW/m^2$. The convective airflow within a compartment may therefore influence extinction once all of the compartment contents have been consumed.

There are few detailed studies in the literature on extinction of smouldering fires, but it is clear that this is challenging due to the difficulties associated with getting water to the hot char and the timescales involved in cooling [51]. The timescales involved to detect and effectively extinguish potential smouldering may also be challenging for fire service responders. Furthermore, the sensitivity of smouldering to parameters such as oxygen flow means that this topic requires further investigation.

Smouldering is important when considering the use of mass timber structural frames in high rise building construction, since smouldering combustion and char oxidation have the potential to continue to:

- release energy which, under certain conditions could lead to further consumption of structural timber or transition back to flaming combustion [5];
- generate significant quantities of toxic gases; and
- further reduce the structural capacity of timber elements after flaming combustion has ceased.

Particular care is therefore needed to ensure that smouldering combustion, which is a complex phenomenon that depends on a range of factors, can be prevented or halted following a fire in a timber building.

4.5 MECHANICAL PROPERTIES

The mechanical properties of timber are known to decrease with temperature [14, 52-54]. Reszka and Torero state that lignin, a key natural polymer component of wood's microstructure, shows the most significant mechanical changes at the lowest temperatures. The glass transition temperature of water-saturated lignin can be as low as 60°C [14], leading to loss of bond strength between fibres, with further mechanical strength losses at temperatures around 100°C. Cellulose is another constituent of timber, and provides timber's tensile strength, the depolymerisation of which occurs in the range of 200°C [14]. Hemicellulose provides timber's compressive strength, and exhibits mass losses beginning at about 180°C [14].

Reductions of mechanical properties of timber can be expected at temperatures much lower than those required for pyrolysis or charring. Detailed analysis of the mechanical response of timber in fire thus requires an understanding of the internal temperature distribution during heating. Because of the above factors, loaded timber members may, under certain conditions, fail at temperatures as low as 50 [28] to 65°C [48], and connection failures may be particularly sensitive [28].

Mechanical property reductions may depend also on: moisture content, pH, heating medium, species, and duration of exposure [48]. When calculating the residual strength of timber, it is important to account for the time-history of temperature, which affects the degree of dehydration and depolymerisation that may have occurred; if heated above 300°C (i.e. charred) then strength is irrecoverable, and above 100°C (i.e. dried) some time is needed to regain mechanical properties due to reabsorption of moisture [56]. The effects of changing moisture content are also important in determining reductions in mechanical properties [52, 53]. Zones of high moisture beneath the char layer may also locally increase timber's plasticity, potentially enabling stress redistribution and improved structural performance [53].

4.5.1 Tensile Strength

Figure 2 shows the normalised reduction in tensile strength of timber with increasing temperature when loaded parallel to the grain. Considerable scatter is evident, and possible reasons for this are the different heating regimes and sample sizes used. In detailed studies, tensile strength appears to reduce gently with temperature up to about 200°C, before decreasing more rapidly at the onset of rapid pyrolysis reactions [52]. Contradictory data on the effect of moisture on tensile strength parallel to grain are given in the literature, ranging from an 18% increase to a 14% decrease upon drying from a moisture content of about 12% [52]. The effect of moisture on tensile strength perpendicular to the grain is also variable, with increases of 50% and decreases of 10% reported upon drying [52]. Strength perpendicular to the grain decreases rapidly, to about 50% at 100°C [52]

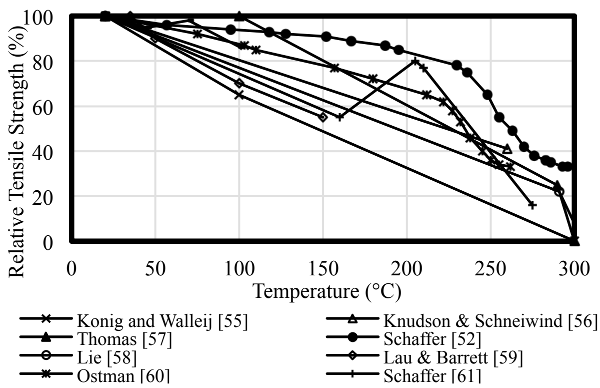

Figure 2: *Tensile strength of timber as a function of temperature*

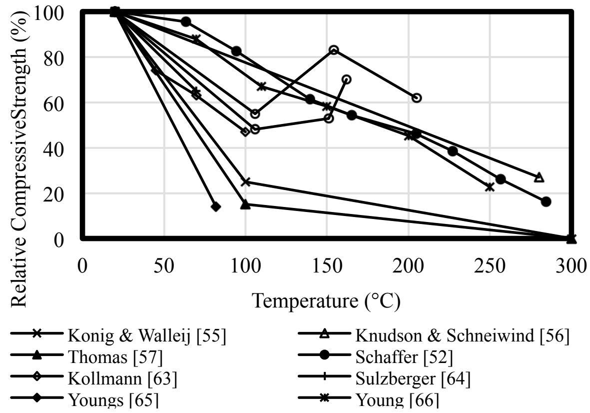

Figure 3: *Compressive strength of timber as a function of temperature*

4.5.2 Compressive Strength

Figure 3 shows the reduction in normalized compressive strength of timber with increasing temperature parallel to the grain. Again, considerable scatter is evident, perhaps due to the different heating regimes and sample sizes in the tests. Compressive strength parallel to the grain appears to be greatly influenced by moisture content, with increases in strength of up to 70-80% for dry wood as compared to wood at 12% moisture content [52].

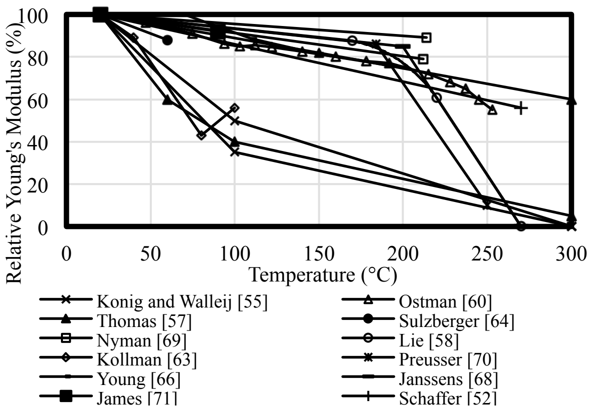

Figure 4: *Modulus of elasticity of timber as a function of temperature*

4.5.3 Modulus of Elasticity and Shear Strength

Figure 4 shows the reduction in normalised modulus of elasticity of timber with temperature. Again, there is clear variability in the data. Elastic modulus parallel to the grain may increase by up to 10% as moisture content decreases from 12% [52]. Modulus of elasticity perpendicular to the grain experiences even greater increases, of 40-50%, with decreasing moisture from 12% [52]. Wet wood exhibits mildly decreasing modulus with increasing temperature up to 225°C, before decreasing rapidly at higher temperatures, whereas dry wood exhibits steady decreases up to 300°C [52]. Perpendicular to the grain the elastic modulus decreases drastically with temperature, dropping to zero at about 100°C regardless of the initial moisture content [52]. Shear modulus increases by about 25% with a decrease in moisture content from 12% to 0%, and decreases by about 50% with increasing temperature up to 80°C [52]. Rapid decreases in Young's modulus at intermediate moisture contents are due to water softening the polymers that make up wood [62]. Shear strength parallel to the grain increases by 20-50% on drying from 12%, but drops rapidly to zero upon heating to 200°C [52]. This may have significant implications for specific failure modes in fire, including rolling shear and connection failure modes that do not govern at ambient.

4.6 REAL STRUCTURAL RESPONSE

Mass timber construction (both solid and engineered) is widely considered to perform well in fire, and many timber structures have survived fire exposures and been repaired for re-use [53]. However, uncertainty exists as to the full frame structural response of high-rise mass timber buildings in severe fires. Existing research suggests that the Eurocode's zero-strength layer analysis method, originally intended for glued-laminated beams, leads to non-conservative predictions of fire resistance for CLT elements tested in standard fire testing furnaces and that the method should be modified [74]. Uncertainties also exist regarding both full-frame and element level failure modes in fire.

Rolling shear failures have been observed in some configurations at ambient temperature [75], but only tensile/flexural rupture has been explored in detail in fire. And as already noted, uncertainty exists as to the relevant mechanical properties of timber at elevated temperature, with conflicting values presented in the literature. The effects of thermal deformations, and their potential impacts on full frame response and delamination, also remain unknown. Timber expands upon heating [31]; however unlike steel or concrete König [31] states that the *effective* thermal expansion of timber is negligible because timber at a 'normal' moisture content of 12% will also shrink as it dries. This mostly offsets thermal expansion [54, 60]. König concludes that isolated member analysis is sufficient for timber structures, and that full frame effects can be reasonably ignored [60]. The rate of shrinkage of timber on drying depends on grain direction, and can be as much as 12% tangentially and 8% radially, but only 0.1 to 0.2% longitudinally [60]. Thermal expansion for dry wood is typically $3.1x10^{-6}$ to $4.5x10^{-6}$/K longitudinally, and timber can therefore be expected to have a negligible net negative expansion coefficient before charring.

Connections can be the crucial area in many mass timber structures [76]. Connection failure modes at normal temperature are typically brittle, even if after significant deformations, and often occur due to splitting parallel to the grain caused by rapid crack growth [76]. In fire, steel components conduct more heat into the cross section and higher charring rates are usually observed in connection areas. Charring of connection side members promotes ductile embedment failures, which are commonly observed in fire tests particularly for connections loaded parallel to the grain. A detailed discussion of timber connection performance in fire is avoided here. Relevant information is available from [77].

5 FUTURE RESEARCH PRIORITIES

Whilst the available design guidance and knowledge have served the structural fire engineering community well up to now for application in conventional low rise engineered timber buildings, the above discussions suggest a range of research needs and opportunities related to timber construction, and in particular the design of tall timber buildings. By careful scientific investigation of the relevant phenomena, likely at multiple scales, the uncertainties can be mitigated, the proposed methodology (i.e. Table 1) harnessed, and design aspirations realised. The following sections briefly summarise the key research needs to support tall mass timber buildings with exposed timber surfaces.

5.1 CHARRING

Pyrolysis and charring rates of timber exposed to non-standard heating are well known to be highly variable, and to depend on a range of materials properties, system properties, and exposure conditions. Charring rates used for design are almost entirely based on standard heating conditions, and may not be directly applicable to some non-standard fire scenarios.

Whilst a great deal of research is available in this area, and there does not appear to be an urgent need for additional fundamental research on this topic, designers ought to be made aware of this potential variability, so that they keep in mind when undertaking simplified structural fire engineering calculations based on notional charring rates. Simple methods should be developed to allow designers to quantify the charring rate for non-standard design fire exposure. This can be done using existing methods and tools.

5.2 FIRE DYNAMICS

The available data on the fire dynamics in compartments with significant areas of exposed timber linings suggest that fires in such compartments can be expected to exhibit: faster fire growth and hence reduced time to flashover; no significant increase in compartment gas temperatures; increased production of volatiles and smoke, resulting in increased amounts and severity of external flaming; increased *total* heat release rate; and the potential for secondary flashover. These phenomena require quantification to mitigate uncertainty.

To determine the necessary design fires and resultant fire dynamics in Step 1 of Table 1, representative small-scale tests are necessary to understand and quantify the auto-extinction properties of wood to apply in design. Multiple large-scale compartment tests (both small and open-plan) are also needed to verify the findings from the small-scale tests, as well as to determine the typical heat fluxes in a compartment with exposed timber, and to verify the material response under these heat exposures, particularly as relates to auto-extinction.

5.3 DELAMINATION

The effects of delamination on effective charring rates under standard fire exposures in furnaces are reasonably well understood, however its causes and contributory factors should be studied more in detail, in order to allow a reliable prediction of delamination. Work is therefore necessary to properly understand and quantify the thermo-physical causes of delamination, as well as the potential consequences of delamination for both fire dynamics and structural response in real buildings.

5.4 SMOULDERING

A particular concern for high-rise mass timber buildings, as compared with equivalent steel or concrete buildings, is on-going smouldering combustion once the compartment contents have been consumed during a fire. This may lead to: release of additional energy leading to further charring or transition to flaming; generation of significant quantities of toxic gases; and further reduction the structural capacity. Research is needed to understand the design actions required to ensure that smouldering combustion can be prevented or halted following a fire in a timber building.

5.5 MECHANICAL PROPERTIES

The available data on the mechanical properties of timber at elevated temperature, which are directly relevant to the rational calculation of member, connection, and structural response during fire, are highly variable and not well understood, particularly under the transient thermal conditions of a fire in which moisture movement and thermal gradients also play significant roles. A great deal of additional research is needed to characterise constitutive material properties for timber under transient heating conditions, such that careful computational modelling can be undertaken with confidence.

5.6 REAL STRUCTURAL RESPONSE

Finally, to investigate the real structural response of engineered timber elements, structural fire testing at small and large scales is necessary. Properly instrumented small-scale element tests under well-defined heating scenarios are needed to determine temperature-dependent mechanical properties for tension, compression, and shear that can be used as input parameters for design models. Large-scale and full-frame tests are also necessary to validate the data obtained, and to determine the variety of possible fire induced failure modes that may occur in real mass timber buildings.

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