

Entry

Smoke Hazards of Tall Timber Buildings with New Products

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Definition: Timber buildings can now stand very tall using new products. As timber materials are expected to be easily ignitable, the fire hazard of timber is a concern. Charring of the timber surface would maintain structural stability, but would also be accompanied by smoke. Although treating timber products with fire retardants would delay the ignition time under low radiative heat flux, toxic combustion products and unburnt fuel would be emitted immediately upon burning. More smoke and higher toxic gas concentrations such as carbon monoxide would be given off upon burning some fire retardants under high flashover heat fluxes. Due to the fast upward movement of smoke under stack effect, spreading of toxic smoke in tall timber buildings would lead to a hazardous environment. Engineered timber consists of derivative timber products. New engineered timber products are manufactured with advanced technology and design, including cross-laminated-timber (CLT), laminated veneer lumber (LVL) and glue-laminated timber (Glulam). The fire behaviour of timber products has been studied for several decades. However, the smoke hazards of using new timber products in building construction should be monitored. The objective of this study is to inspire stakeholders in fire safety of timber buildings, inter alia smoke hazards, to use new timber products to build tall buildings.



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1. Introduction

Timber buildings using engineered wood have become more and more popular [1–4] over the past few decades due to its sustainability, light weight, lower amount of greenhouse gas emissions, energy demand and shorter duration in the construction phase. Lower amounts of greenhouse gas emission and energy demand are conducive to producing a green environment. Timber buildings can be much taller than before [5–8], with new products including cross-laminated-timber (CLT), laminated veneer lumber (LVL) and glue-laminated timber (Glulam). Fire safety concerns for timber buildings have been reported in many open forums [2,9–12] for 20 years. With the advancement of technologies and designs of engineered timber products throughout the last 25 years, wood fibre is used in new engineered timber products [4]. The strength and stiffness of the new products are often achieved by using thin veneers or timber studs and applying adhesives to form composite materials with greater structural strength than the individual elements [13]. CLT is an engineered composite product that consists of multiple layers of boards that are adhered perpendicularly to each other to achieve strength in multiple directions. In some countries, it is referred to as “solid timber”, “solid timber panels” or “mass timber”. It is most commonly used for load-bearing walls and floors. LVL is the most widely used engineered structural composite lumber. It consists of multiple layers of thin wood veneers (approximately 3 mm thick) that are laminated parallel to each other under heat and pressure. The resulting LVL product demonstrates improved structural performance compared to solid timber members. Glulam is an engineered composite product that

consists of smaller pieces of stress-graded wood (nominally 50 mm × 100 mm) that are adhered, or laminated, together. This produces a product that is stronger than solid timber. Glulam elements are most commonly used as posts and beams [13]. Although the fire behaviour of timber products has been well analysed in many studies, the fire hazard of timber remains a concern and constitutes an obstacle to its use in construction. Wood can be ignited easily to emit heat and smoke, which consists of toxic combustion products and unburnt fuel. The smoke generated will spread to different parts of a tall timber apartment due to stack effect. Although charring of the timber surface would maintain structural stability, smoke hazard is a threat. There is conflict commonly existing between fire safety and environmentally friendly design.

2. Fire-Resisting Construction Requirements

From the 1950s to 1980s, there had been many big fires involving buildings of timber construction in Hong Kong, resulting in the severe injuries of many residents and firefighters. The Shek Kip Mei Fire on Christmas Day in 1952 destroyed about 2580 single-storey timber houses along with about 164,000 m² of hillside. Such timber buildings did not have any resisting period for containing the fire. They were burned down within a very short period of time and spread to the nearby buildings rapidly, especially buildings constructed on the slope and in dry and windy seasons.

In order to solve the problem, the Government of Hong Kong adopted the Fire Resisting Construction requirements for building construction, which were first referenced from the London County Council (LCC) By-laws 1952, 1964 and subsequent amendments as stipulated in the Buildings Ordinance 1955. As required by the building authority of Hong Kong, every building should be compartmented by walls and floors to inhibit the spread of fire. All roofs, together with the members forming the roof structure, should be constructed with non-combustible materials. Combustible materials are not allowed as structural members in buildings. Additionally, application of timber for building construction is strictly controlled and very tight testing standards on assessing thermal fire aspects are needed. Therefore, using timber as a key building material in tall buildings is justified in terms of fire safety.

3. Fire Studies of Timber

The fire behaviour of timber buildings is, among other factors, dependent on the fire behaviour of wood and a lot of related studies have been reported in the literature [9,10,12]. Modelling the thermal degradation of structural wood members exposed to fire was proposed by Janssens [14]. In addition, the effect of size, shape and pyrolysis conditions on the thermal decomposition of wood particles and firebrands was reported by Atreya et al. [15]. On the other hand, Richter et al. [16] conducted research on the effect of chemical composition on the charring of wood across scales.

The moisture content of timber will be changed if the ambient relative humidity varies [17]. The higher the moisture content, the more difficult it is to ignite timber. Timber can be ignited easily at low relative humidity. Treating timber products with appropriate fire retardants would delay [18] the ignition time under low radiative heat flux. However, the delay in time in igniting the plywood materials treated with fire retardants would not be significant at high heat radiative flux [19]. The materials were also burned under post-flashover fire as observed in past fire records. More smoke and higher amounts of toxic gas such as carbon monoxide were given off upon burning paints, including fire retardant paints.

Many open forums were held on tall timber buildings for multiple uses [2]. A case study of the fire safety of tall timber buildings in Hong Kong was reported by Chow et al. [12]. Combustible materials are basically not allowed as construction materials in many places including Hong Kong, after painful lessons learnt from big fires with houses constructed of timber.

Recently, real-scale fire tests of compartments constructed with CLT slabs and glulam beams and columns were reported by the RISE Research Institute of Sweden in Brandon et al. [20]. The results of the tests show that timber fires decayed constantly post-flashover until four hours after ignition and reached radiation temperatures significantly below 300 °C under environments without the provision of sprinkler system. Concerns of the structural robustness of tall timber buildings in fire and the general approaches with regard to fire design were discussed by Schmid et al. [21]. Advanced full-scale fire experiments on large timber buildings are not common due to the limitations of resources and concerns of safety. Nevertheless, there have been several full-scale fire experiments performed over the world, as cited in Brandon and Östman [22] and Östman et al. [23].

A detailed report of a series of full-scale fire experiments on a two-level mass timber apartment was presented by Hoehler et al. [24]. This is the most detailed scientific study of fire testing of timber buildings up to now. The effect of coverage of wood surfaces with gypsum wallboard in the fire test was investigated under the activation of a sprinkler system. Su et al. [25] conducted a full-scale fire test of compartments constructed of 5-ply CLT. It was found that the use of gypsum board is very important in protecting CLT in a fire and that the ventilation conditions also play an important role. The need to use heat-resistant adhesives in CLT to minimize delamination was also suggested.

A report on real-scale fire tests of timber buildings was presented by Li et al. [26] at the WCTE Conference 2016. It was found that the heat release rate in the fire tests depended on the unprotected area of the CLT surface in a room. CLT delamination and charring rate and the performance of gypsum boards were also studied. Full-scale tests on the fire resistance and charring behaviour of laminated timber structural systems used as walls and floors in mid-rise and tall timber buildings were conducted by Lindsay et al. [27].

Compared with full-scale burning tests, computer modelling is an inexpensive way to investigate fire behaviour in a compartment (Chow [28–30]). There are numerous reports on computer modelling in relation to fire of timber members and wood buildings, as reviewed by Östman et al. [23]. Fire modelling for the effect of sprinklers on fires of timber structures was presented in a report by Dembsey et al. [31]. Kmiecik [32] used the Fire Dynamics Simulator (FDS) to determine the time-varying spatial map of temperature of a timber beam exposed to fire. The FDS results were then used to determine the load-bearing capacity of timber beams, employing the SAFIR software. Tian et al. [33] combined FDS and statistical techniques, claiming that the results can be used to study the pyrolysis of timber buildings. Dârmon and Suciu [34] reported a simulation of smoke ventilation and a strategy for a timber building on fire using FDS.

4. Smoke Hazards of Wood and Wood-Based Products

Wood is a natural polymer with carbon, hydrogen, and oxygen, with lower percentages of nitrogen from cellular proteins and small quantities of other elements that remain as an ash when wood is burned, while engineered wood composite products behave very differently from their primary wood precursors. The introduction of glues and resins into the structural materials changes the chemistry of those materials. The relatively simple combustion chemistry of cellulose is complicated by the presence of petroleum-derived plastic resins, some of which may contain aromatic rings, halogens, epoxies, and other unsaturated hydrocarbon constituents. This affects heat output, flame spread rate, smoke composition, and smoke density during a fire involving these materials [35].

During wood burning, the smoke released from fire consists of a mixture of particles and chemicals produced by incomplete burning of carbon-containing materials, including carbon monoxide, carbon dioxide and particulate matter (PM or soot). Two of the major agents in smoke that can cause health effects are carbon monoxide gas and very small particles (fine particles, or PM_{2.5}). These particles are two and a half (2.5) microns or less in size (25,400 microns equal an inch) and individual particles are too small to be seen with the naked eye [36]. People who are exposed to smoke may be harmed as a result of exposure to toxic gases, elevated temperature, or radiant energy. For short duration exposures (on

the order of 1 to 2 min), a carbon monoxide concentration of 0.1 to 0.8 percent may cause humans to become incapacitated while walking or being involved in a similar level of activity [37].

The majority of fire deaths result directly or indirectly from the presence of smoke. Statistics originating from the UK and USA show that over 80 percent of all recorded fatalities were caused by smoke inhalation. These deaths could have resulted from a deficiency of oxygen, injury caused by the high temperature, the presence of toxic and corrosive gases, or the high concentration of solid matter. Most were due to a combination of these causes. Indirectly, the loss of visibility in smoke may delay or prevent escape, and people are then killed by fire and/or by prolonged exposure to smoke [38]. A reduction in visibility due to smoke may cause disorientation, tripping over obstructions, or reduce the walking speed of occupants during evacuation, thereby increasing the egress time [37].

5. Use of Timbers in Multi-Storey Building Construction over the World

A list of multi-storey buildings constructed using timber, CLT or glulam is compiled [39] in Table 1. The height of such timber buildings exceeds the limit stated in the codes of some countries. This is also essential to consider in terms of safety. For low-rise buildings (up to eight stories), occupants can travel downstairs to a place of safety on the ground floor with less time for evacuation. However, for tall buildings, firefighting, rescue or complete evacuation is much more difficult, especially if the fire occurs on the upper floors with occupants stranded on such floors. This is disastrous, regardless of the building materials. For taller buildings, full or partial encapsulation is required in order to satisfy the fire resistance requirements.

Table 1. List of current multi-storey timber buildings.

Building Name	Stories	City, Country	Year of Completion
Mjøstårnet	18	Brumunddal, Norway	2018
HAUT	21	Amsterdam, The Netherlands	2019
Brock Commons	18	Vancouver, Canada	2017
Treet	14	Bergen, Norway	2015
Origine	13	Quebec, Canada	2017
Framework	12	Portland, Oregon, United States	2018
Leader's Building	12	Wellington, New Zealand	2018
25 King	10	Brisbane, Australia	2018
Trafalgar Place	10	London, United Kingdom	2015
Forte	10	Melbourne, Australia	2012
Dalston Lane	10	London, United Kingdom	2008
Moholt 50/50	9	Trondheim, Norway	2016
Cenni di Cambiamento	9	Milan, Italy	2013
Stadthaus	9	London, United Kingdom	2009
Murray Grove	9	Hackney, Finland	2009

Source: ref. [39].

6. Fire Safety Concerns on Timber Buildings and the Way Forward

Up to now, fire safety research on timber buildings is mainly focused on timber building materials, low-rise timber buildings, and timber building groups in rural areas in Japan and in Asia-Oceania countries because of earthquake threats or economic problems. There are strong reservations on approving buildings constructed of timber in some places [2,12] due to many previous large fire and explosion disasters. The following concerns on the development of timber buildings, especially multi-storey timber buildings, can be identified:

- Public perception.* The fire safety of timber buildings, even up to very recently, has been a major concern [2,12]. This forms an obstacle to the development of timber buildings according to surveys in Australia and China [40,41]. Compared with conventional concrete buildings, the knowledge of fire safety of timber buildings may not be adequately digested by professionals even in developed countries [42,43].
- Training for professionals.* Besides the perception of the fire safety of timber buildings, another obstacle is the lack of provision of training for professionals in this area. As

multi-storey timber buildings are becoming more popular, the training of professionals in the fire safety of timber buildings is an important area in the development of the building industry. There are articles on wood and evolving codes for timber buildings [44]. A presentation on knowledge related to the fire safety of tall wood buildings was delivered by the Wood Products Council [45]. In response to the higher occurrence rate of fire incidents during the construction phase of timber buildings, the Structural Timber Association has published a design guide with particular guidance on separating distances during construction [46]. Others reported [47,48] fire safety issues of timber buildings, or provided educational and information resources on the fire safety of timber buildings.

- (iii) *Research.* More research should be carried out to identify the difference in fire characteristics, related safety issues, and rescue strategy between concrete buildings and timber buildings. Without extensive research work to identify the difference, it is very difficult and also unreliable to translate current knowledge on fire safety for conventional buildings to timber buildings. Specifically, smoke spread in tall timber buildings, as discussed in this paper, has not yet been handled thoroughly. While the behaviour and performance of timber products such as CLT and glulam have been quite extensively studied, the structural integrity of a timber building has not been adequately investigated [49]. In fire hazard assessment, thermal effects under an agreed design fire described by heat release rate such as 10 MW was studied. Smoke hazards were neglected in many projects [50] assessing fire hazards, thus erroneously and dangerously giving longer Available Safe Egress Time [51,52].
- (iv) *Codes and regulations.* Regulations, codes and guidelines specifically for the fire safety of timber buildings have to be formulated. Recently, Kincelova et al. [53] proposed a building–information–modelling (BIM) approach to improve fire protection aspects in compliance with fire safety regulations in timber buildings. As reported by Nomura et al. [54], the Japanese government has been promoting wider use of wood buildings. Construction of larger-scale timber building is allowed recently in many other countries. Requirements of external fire spread between buildings and impact on fire safety codes were studied. As reported by Hagiwara [55], Building Standard Law in Japan was reviewed in 2014 to include large buildings constructed with timber, and in 2018, for the promotion of wood utilization. Future directions will be on further relaxation and promotion of timber construction and members. Fire spread and evacuation requirements are imposed. Assessing smoke toxicity is not yet observed, apart from enhancing evacuation strategy.

The difference in firefighting, rescue and evacuation plans between conventional buildings and timber buildings should be identified. Education of relevant professionals and the general public on the fire safety issue of timber buildings is important for the healthy development and advancement of the timber building industry. The targeted group includes building architects, building engineers, fire safety engineers, firefighters, surveyors, insurers, estate managers, and the interested public. As tall timber buildings are relatively new, the most important knowledge to be acquired is the difference in fire characteristics between conventional buildings and timber buildings. Appropriate fire safety management [56–58], particularly a feasible and pragmatic action plan, has to be worked out.

7. Recommendation on Assessing Smoke Hazard

The ignition time, peak heat release rate, average heat release rates 60 and 180 s after ignition, total heat release rate, mass loss percentage, total smoke release, carbon monoxide and carbon dioxide can be measured in a cone calorimeter. In addition to modelling timber fire [59], parameters deduced from the cone calorimeter are useful for helping the authorities set up regulations for assessing the fire behaviour of materials. Arbitrary scales were proposed [60] and discussed for fire-retarded timber materials on the propensity to flashover and total heat release rate [18], which are good starting points

to develop appropriate fire codes supported by burning tests. Key parameters on smoke, carbon dioxide and carbon monoxide concentrations should be measured. The “lethal concentration of the fire effluent emitted to produce death in 50% of test animals for a specified exposure time” and the fractional effective dose based on the cone calorimeter data can be determined [61,62].

As reported before [63], three parameters (x , y and z) describing fire hazards in burning timber can be deduced from cone calorimeter tests to rank fire risk. Parameters x and y are the thermal aspects in flashover propensity and total heat released per unit surface area, and z is smoke toxicity calculated from peak carbon monoxide concentrations [31].

The first parameter is the flashover propensity x (in $\text{kWm}^{-2}\text{s}^{-1}$) given by the peak heat release rate ($pkHRR$) and time to ignition (TTI):

$$x = \frac{pkHRR}{TTI} \quad (1)$$

The second parameter is the total heat releases (THR) (in MJm^{-2}):

$$y = THR \quad (2)$$

The peak Fractional Effective Dose (FED) is calculated from the peak concentration of CO and CO_2 , denoted by $[\text{CO}]$ and $[\text{CO}_2]$, and their toxic potency, “lethal concentration of the fire effluent emitted to produce death in 50% of test animals for a specified exposure time”, with LC_{50} denoted by LC_{CO} and LC_{CO_2} :

$$FED = \frac{[\text{CO}]}{LC_{\text{CO}}} + \frac{[\text{CO}_2]}{LC_{\text{CO}_2}} \quad (3)$$

Since LC_{CO_2} is very large, FED is calculated only from the peak concentration of $[\text{CO}]$ denoted by $pk[\text{CO}]$ and taking LC_{CO} as 5000 ppm (e.g., [56–59]):

$$FED = \frac{pk[\text{CO}]}{5000} \quad (4)$$

LC_{50} is the fire effluent emitted to produce death in 50% of test animals for a specified exposure time. It is given by the specimen mass loss Δm , bench-scale volume in a cone calorimeter ΔV (0.01 m^3), and the fractional effective dose (FED) as:

$$LC_{50} = \frac{\Delta m}{FED \cdot \Delta V} \quad (5)$$

The parameter z is used to rank smoke risk and is taken as LC_{50} , i.e.,

$$z = LC_{50} \quad (6)$$

Applying fire retardant additives can reduce the values of thermal parameters x and y . However, z would be increased because fire retardation might result in incomplete combustion and, hence, a higher concentration of carbon monoxide. Building height can generate strong stack effects, which can become a serious factor in smoke movement [64]. Under stack effects in a high-rise building, vertical natural air movement through the building is caused by differences in temperatures and densities between the inside and outside air [37]. Strong stack effects [65] would facilitate a relatively fast smoke movement rate in taller buildings, resulting in building occupants on upper floors being susceptible to having less time for evacuation. Fire hazards of timber partitions only [66] provided numerous problems. The hazards will be much more serious for tall timber buildings and should be monitored. Note that without appropriate fire safety management [67], evacuation in tall buildings with high occupancy would be unsatisfactorily slow.

8. Conclusions

Fire safety is a great concern when using timber as construction materials for achieving a sustainable environment. Nowadays, there is a greater demand for tall buildings. This demand coupled with the increasing popularity of using timber as building materials leads to an urgent need to study the problem of the fire safety of tall timber buildings. Although the fire behaviour of timber products has been well-studied, research on the fire safety of tall timber building as a whole is almost absent or only in its infancy as presented above. It is obvious that the fire resistance rating of walls, floors and fire compartment area or space volume to inhibit the spread of fire are very different for timber buildings as compared with reinforced concrete buildings. Thus, more full-scale burning experimental work is required to verify performance and justify the preventive measures of timber buildings under standard or non-standard fire exposure, to make timber buildings more safe. Such experimental data are useful for developing appropriate fire models for tall timber buildings. Training of professionals (including engineers and fire safety personnel) and the formulation of regulations, codes and guidelines are also of equal importance to ensure a safe tall timber building.

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