Timber Building: A Safe Green Structure or a Concern in Fire Safety?

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Abstract

In the past, most high-rise and large multi-use or non-residential buildings were constructed from concrete and steel. Recently, timber is also attracting the interest of the construction industry for achieving sustainability. The combustibility of timber is a concern in fire safety and constitutes an obstacle to its wide-spread use in construction of buildings, especially high-rise buildings, despite its attractive properties. Knowledge of potential fire hazards and the corresponding appropriate design in fire safety measures are pre-requisites. Education and promotion by fire safe timber buildings is essential for overcoming the barrier arising from fire safety concern of timber. The intent of this paper is to consolidate the latest review to explore the way forward for further study of the fire safety of timber buildings.

Keywords: Timber buildings; Fire tests; Simulation; Cross-laminated timber; Public concerns

1. Introduction

Timber buildings have attracted more attention again (Yue 2020) due to its sustainability. Timber-related products, like cross-laminated timber (CLT) or glue-laminated-timber (GLT), commonly known as glulam, are used as building materials, particularly in constructing high-rise buildings. The major threat of using timber in building construction is its combustibility. For example, the fire safety concern for timber partition was reported by Chow et al. (2005). This paper mainly focuses on fire safety of timber buildings.

The fire behavior of timber buildings is, among other factors, dependent on the fire behavior of wood. Modeling of thermal degradation of structural wood members exposed to fire was proposed by Janssens (2002). 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. (2017). On the other hand, Richter et al. (2019) conducted a research on the effect of chemical composition on the charring of wood across scales.

There are many studies about the fire behavior of timber-related structures as reported (Chow et al. 2018a, 2018b; Cheng et al. 2022). Risk assessment of a timber frame building by using CRISP simulation was performed by Björkman and Mikkola (2001). Post-flashover fires in light and heavy timber construction compartments were compared in a study by Hakkarainen (2002). Modelling and tests on the behavior of CLT when exposed to fire was reported by Schmid et al. (2010). Charring of the timber surface would maintain structural stability, but would also be accompanied by smoke aa reported (Cheng et al. 2022). Although treating timber products with fire retardants would delay the ignition time under low radiative heat flux, 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.

A case study of the fire safety of high-rise timber building was reported by Chow et al. (2018a, 2018b). This case study identifies the potential issues related to using timber as structural elements for high-rise buildings and research activities required to determine appropriate fire safety provisions. Recently real-scale fire tests of compartments constructed of CLT slabs and glulam beam and column were reported by the RISE Research Institute od Sweden (Brandon et al. 2021). 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 ^{o}C without the use of sprinkler system. Concern of structural robustness of tall timber building in fire and the general approaches with regard to fire design were discussed by Schmid et al. (2020).

The present work intends to give an overview in relation to the fire safety issues of multi-story timber buildings. It attempts to give a broader picture of different aspects of current fire safety issues of multi-story buildings.

2. Methodology

In the present paper, only literatures in multi-story timber buildings and related fire safety issues in the period 2000 to June 2020 indexed by Scopus using keywords: fire and safety and timber buildings are reviewed. Additional information is acquired from Google and Wikipedia. The source of literature includes journal paper, conference paper, technical report and monographs. The results of literature search are grouped into four parts: (i) recent reviews and reports on the fire safety of timber buildings, (ii) the fire resistance of timber materials used in multi-story timber buildings, (iii) the use of timbers in multi-story building construction over the world, (iv) study of fire safety of timber buildings by full-scale fire experiments and by computer modeling, and (v) fire statistics of timber buildings.

3. Recent reviews and summary reports on the fire safety of timber buildings

There are a number of review papers or reports on fire safety of timber buildings, especially multi-story timber buildings. The performance of timber buildings exposed to fire was reviewed by Buchanan (2000). The difference of fire behavior between light timber building and heavy timber building was described. The impacts of pre- and post-flashover fires were also identified. Frangi and Fontana (2005) conducted a review on the fire performance of timber structures when natural fire occurs. More recently, the fire resistance of timber structures was reviewed by Buchanan et al. (2014) in a report for the National Institute of Standards and Technology. For the fire safety of tall wood buildings, the Fire Protection Research Foundation has published two reports, one summarizing the current knowledge and understanding of fire safety in timber buildings, especially tall timber buildings (Gerard et al. 2013), the other on the contribution of CLT to compartment fires (Brandson and Östman 2016). A summary of the fire protection foundation report on the fire safety challengers of tall wood buildings was drafted by Barber and Robert (2015). As pointed out in a review by Östman et al. (2017), the possibility for an increased use of timber in buildings relies on the provision of adequate fire safety. The review delineates the opportunities and challenges to reach this goal by implementing Fire Safety Engineering and Performance Based Design principles. On the other hand, a recent review on the fire safety of buildings made of CLT in Canada was reported by Su (2018).

4. Fire Resistance of Timber Materials in Building

Cross-laminated timber (CLT) and glued laminated timber (glulam) are the major materials used timber buildings. Owing to the concern of combustibility and also to the more complex nature of timber materials in building, the fire resistance of these timber elements is still a hot current research topic. Research in fire resistance of laminated timber elements not only involves the performance of timber, but also the cladding or coating, and the adhesive. Some of these most recent studies are as follows.

Fire design of CLT has been investigated by Schmid et al. (2019), Östman et al. (2018) and Klippel et al. (2016) while the fire resistance of mass timber shaft was reported by Osborne and Dagenais (2015). The fire resistance of CLT and glulam beams was reported by Darmon and Lalu (2019) and Fahrni et al. (2019) while the fire behavior of CLT panels was studied by Wang et al. (2020) using experimental and numerical analysis. The fire resistance of full-scale unprotected CLT floor assemblies with two adhesive systems was investigated by Muszynski et al. (2019). A meta-analysis of the fire resistance of CLT compression elements with respect to structural capacity was presented by Wiesner and Bisby (2019). On the other hand, detailed full-scale fire resistance tests of CLT panels using thermocouples and deflection gauges were reported by Lindsay et al. (2012). Test of CLT in compartment fire was performed by Su et al (2018). The effect of fire retardant in the fire behavior of timber products was reported by Chow et al. (2002, 2012). On the theoretical side Chen et al. (2020) developed a constitutive model, WoodST, for numerical simulation of wood-based materials and connections under forces and fire.

The type of adhesive used in CLT was shown to have significant effect on the deterioration of structural stiffness of the CLT beam when exposed to non-charring temperatures (Wiesner et al. 2020). The performance of different types of adhesives with different 2-ply configurations in fire was reported by Hasburgh et al. (2016). They found that melamine formaldehyde and phenol resorcinol formaldehyde performed well while the “Long-Long-Cross” configuration resulted in uneven charring. In order to examine the integrity of CLT members, Zelinka et al. (2019) studied loss in strength and stiffness due to deterioration of four adhesive bonds below the charring temperature. The performance of adhesives in glulam beams after short fire exposure was reported by Quiquero et al. (2018). They showed that the commonly employed “zero-strength layer” guidance may be under conservative. On the other hand, Janssens and Joyce developed a performance assessment methodology for adhesives used in CLT (2017).

The effect of thin intumescent coating on timber samples exposed to a radiant heat flux of 50 kW/m^2 was investigated by Lucherini et al. (2019). They showed that the coating could delay the onset of charring and reduce the subsequent charring rate. On the other hand, Hasburg et al. (2016) investigated the effect of encapsulation on the fire resistance of CLT and concluded that the encapsulation method has significant effect on delaying the onset of fire of the wood element and also on reducing the charring rate.

Less research was reported on the environmental effect on the charring behavior of timber under real fire scenarios. In this connection, the influence of oxygen content and gas velocity was investigated by Schmid et al. (2018).

It can be seen from these recent publications that the research on the behavior of timber elements as building materials continues to be a hot topic among scientists and professionals, though ample information and data have accumulated over the years. However, as pointed out in a recent review by Barlett et al. (2019), there is still a gap between the science and knowledge in the fire performance of timber elements and their applications in real buildings. This is a big area awaiting in-depth research and could be the bottle neck in the development of high-rise timber buildings.

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

Timber-framed buildings appear in various countries over the world, such as Canada, the United States, the United Kingdom, Australia, and Europe, etc. Some codes stipulate the restrictions on the maximum number of stories of a timber building. For example, the maximum number of stories of a timber building can be only 5 for a building without the provision of sprinklers (NFPA 5000, 2012) and 8 with the provision of sprinklers (2012 Federal Building Code, Germany). Under this code, the majority of buildings of 7 to 8 story-high have their construction completed in several countries in the past few years. One example of such a green building is the Carbon 12 building in Portland USA, of height 8 stories as reported in Yale Environment 360 (2019). The tallest timber building at present is the Mjøstårnet in Norway, which is 85.4 metres high and built of cross-laminated timber (CLT). This building is of 18-story and contains hotel, office space, restaurant, apartment and even swimming pool. A list of multi-story buildings constructed using timber, CLT or glulam had been compiled (Cheng 2022).

There are proposed timber buildings in different countries made of mass timber of height 18 stories or above. Table 1 shows some of the multi-story timber buildings which are under construction, planned or under research.

6. Study of Fire Safety of Timber Buildings by Full-Scale Fire Experiments and Computer modeling

6.1 Full-scale fire experiments

Full-scale fire experiments on large timber buildings are not common due to difficulties arising from resources and safety. Nevertheless there were several full-scale fire experiments performed over the world as cited in Brandon and Östman (2016) and Östman et al. (2017). In these two reviews the papers or reports cited are up to 2014. Thus in the following the focus is mainly on work reported after 2014, except in some special cases. Full-scale fire experiments were carried out for full-scale multi-story wood buildings or for full-scale single rooms in wood buildings.

Fire tests on a 3-story school building in Japan were carried out by Hasemi et al. (2014). The building was mostly made of light timber. When the building was protected with gypsum plasterboard, fire damage could be minimized. In addition, the tests had two types of fire resistance grading: fire resistive construction, which required structural stability of structural elements during and after a fire including the cooling phase, and fire preventive construction, which required structural stability for a certain duration. Non-combustible structural elements required a 3-hour cooling phase after 1-hour fire resistance test but for combustible elements, the cooling could be as long as 24 hours.

Full-scale burning test of a compartment to evaluate the fire performance of protected CLT and nailed laminated timber construction was carried out by Janssens (2015). A detailed report of a series of full-scale fire experiments on a two-level mass timber apartment was presented by Zelinka et al. (2018). This is the most detailed scientific study of fire testing of timber buildings up to now. The effect of coverage of wood surface with gypsum wallboard in the fire test was investigated, together with the efficacy of sprinkler activation for fire suppression. In an another research (Hoehler et al. 2018) on 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. It also suggested the need of using heat-resistant adhesives in CLT to minimize delamination.

Full-scale tests on the fire resistance and charring behavior of laminated timber structural systems used as walls and floors in mid-rise and high-rise timber buildings were conducted by Lindsay et al. (2019).

Room fire tests with and without encapsulated timber structures were conducted in European countries (Finland: Hakkarainen et al. 2002; Greece: Kolaitis et al. 2014; Switzerland: Frangi et al. 2005; Italy: Frangi et al. 2008, Stein and Winter 2008). The room temperature during fire was similar in all cases. The important conclusion is that with adequate protection of the timber structure and/or installation of fast-response sprinklers, fire safety objectives for timber structures can be fulfilled. Another reported case was a 3-story building made of CLT panels exposed to natural fire (Frangi et al. 2008). The CLT panels were protected by one or two layers of non-combustible gypsum plasterboards. The results revealed that fire spread to other rooms could be reduced. Full-scale timber building fire tests were carried by researchers at the Technology University of Munich (Stein and Winter 2008). Two fire rooms with normal fire load density were used in the tests. The study by Kolaitis et al. (2014) showed that gypsum plasterboards offer much better fire protection than wood-based panels. Test on the spread of fire through joints and penetrations in CLT buildings was reported by Karuse (2018). The results showed that the joints and penetrations as well as the tested door and windows were capable of isolating the compartment in terms of spreading of heat and smoke.

Some of the more recent reports on these full-scale fire tests are summarized in Table 2.

Based on the above tests, more tests are required to provide more complete information on fire severity and safety as there is a tendency of having high-rise timber buildings. Examples of further work should include (i) the determination of the contribution of CLT to the fire severity for non-standard fire exposure, (ii) fall-off time of claddings under non-standard fire exposure, (iii) charring rates of CLT by considering the effects of different adhesives, (iv) effect of wooden façade claddings on the exterior fire spread of multi-story buildings with flame coming out from a broken window after flashover and (v) the influence of active fire protection system in structural fire performance and external spread of flame in a timber building.

7. Fire Safety Study of Timber Buildings by Computer Modelling

Compared with full-scale burning tests, computer modelling is an inexpensive way to investigate fire behavior in a compartment (Chow 1995a, 1995b; 1996). To predict the structural performance of a timber building in fire, one needs to construct three models and their interactions: (i) the fire model (Hietaniemi and Mikkola 2010, McGrattan et al. 2014), (ii) the thermal model (Buchanan et al. (2014), EN 1995-1-2, Eurocode 5), and (iii) the structural model (Buchanan et al. (2014), White et al. (1981), König and Walleij (1999)). The important inputs and outputs for these models and the flow chart relating these models were proposed by Buchanan et al. (2014).

There are numerous reports on computer modeling in relation to fire of timber members and wood buildings as reviewed by Östman et al. (2017). In addition to these reports, Ek and Andersson (2017) of the Luleå University of Technology used a computer program TASEF (Temperature Analysis of Structures Exposed to Fire) to study the temperature distribution and charring penetrations in timber assemblies exposed to parametric fire curves. Fire modeling for the effect of sprinklers on fire of timber structures was presented in a report by Dembsey et al. (2018). It is interesting to note that in structural modeling of timbers in fire, Werther et al. (2012) examined and compared the efficacy of different finite-element software, including ANSYS, SAFIR and ABAQUS. Kmiecik (2018) 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 beam employing the SAFIR software. Thi et al. (2018) reported simulation of the fire integrity resistance of gypsum-faced CLT wall using ABAQUS together with a self-developed subroutine UMATHI. Tian et al. (2016) combined FDS and statistical technique, claiming that the results can be used to study fire pyrolysis of timber buildings. Dârmon and Suciu (2018) reported simulation of smoke ventilation and strategy of a timber building on fire using FDS.

A summary of computer simulation studies on fire and fire spread in timber buildings is given in Table 3.

In the fire safety study of timber buildings, the structural performance of the building is of great importance. The flow chart presented in Buchanan et al. (2014) suggests a sequential or piecewise approach in the modelling. It is perhaps a bit ambitious but might yield more realistic results if the approach is an integrated one, where the time evolution of the structural performance of the timber building can be predicted in one program, given the location and size of fire, and details (material and geometric) of the timber building.

8. Fire Statistics Involving Timber Buildings: Some Observations

A review of fire statistics from the UK and the USA is provided by the Fire Protection Association, UK (2011), and by Gerald et al. (2013). The statistics in the review illustrates that the fire risk of timber frame is higher during the construction phase than that of a building having its construction completed. Firstly, there are different ignition sources in the construction sites, including welding, electricity, careless disposal of smoking materials, etc. In addition, the construction sites would store different types of materials, some of which may be combustible, including unclad timber members, and hence higher risk of catching fire. Poor housekeeping could increase the risk of catching a fire. Furthermore, construction sites without passive fire protection, such as fire resistant walls or other fire protection systems could be a source of fire risk.

8.1 United States

Statistics in the United States reveals that for buildings which utilized steel and concrete for walls, floors and structural framework (protected or unprotected), the number of fatalities was lower in residential buildings than in non-residential buildings. On the contrary, when the building had masonry walls, but the floors, roof and structural framework were made of timber or other combustible materials, more fatalities occurred in residential buildings than in non-residential buildings. If the materials were unprotected, the effect was much more evident. The same happened if the building was made of light timber frame. In addition, if the building was made of heavy timber, for example, cross-laminated timber CLT, the walls were made of masonry but the interior wood consisted of large timber, no fatalities were recorded. This indicates that the use of heavy timber is effective in reducing injuries in the event of fire.

8.2 United Kingdom

According to a publication about fire statistics in timber frame buildings in England in 2011, buildings made of light timber frame had significantly less fire risk, compared with those constructed using traditional building materials and construction techniques (Fire Protection Association, Building, Design and Management, UK 2011). This applies to buildings having construction completed and those under construction. Similar to the case in the United States, buildings under construction had a significant higher fire risk than those had their construction completed. An often-cited example is the complete burnout of a light timber building under construction in Salford, UK in 2013 reported in Manchester Evening News. For all residential buildings in England, when there is a fire, only an area of 5 m^2 or less was damaged by fire in most timber frame residential buildings. This means the severity of fire in timber frame buildings is not as serious as expected. For non-residential buildings in England, similar results were observed as in residential buildings.

8.3 Sweden

Record of fire incidents in timber buildings in Sweden from 1998-2104 was extracted by Östman (2016) from a report of the Swedish Civil Contingencies Agency (MSB 2015). Based the statistics, it is found that the fire incidence rate in modern multi-story timber buildings is less than the overall average of all kinds of buildings. The reasons could be that these timber buildings are relatively new and have been designed according to modern fire safety regulations.

8.4 New Zealand

Statistics of fire incidents of timber buildings (three stories or higher) in New Zealand in the period 2000 to 2016 was compiled by Brandon et al. (2018) based on the data from the New Zealand Fire Service. Using 1991 as the demarcation year, Brandon et al. (2018) found that for buildings constructed before 1991, there is a higher frequency of large fire damage in timber buildings compared with other types of buildings, but this difference disappears for buildings constructed after 1991. The authors attributed this to better fire safety design for the newer timber buildings. This observation seems to assert that when proper fire safety design is implemented, timber buildings are as safe as other types of buildings with respect to fire.

Another interesting observation from the New Zealand data is related to water damage in firefighting. It is found that the frequency of water damage that extended beyond the fire cell of origin was lower in modern timber buildings (>1991) than in other types of buildings.

9. Discussion

Concerns on the development of timber buildings for sustainability were discussed in Cheng et al. (2022) on public perception, training for professionals and targeted research.

Way forward to fire safety of timber buildings needs careful study in future research on providing fire safety (Chow 2015). Education of the related professionals and the general public in the fire safety issue of timber buildings is important for a healthy development and advancement of the timber building industry. The targeted group includes building architects, building engineers, fire safety engineers, fire fighters, surveyors, insurers, estate managers, and the interested public. As multi-story timber buildings are relatively new the most important knowledge to be acquired is the difference in fire characteristics between conventional buildings and timber buildings. Regulations, codes and guidelines specifically for the fire safety of timber buildings have to be formulated. Recently, Kincelova et al. (2020) proposed a building-information-modeling (BIM) approach to improve fire protection aspects in compliance to fire safety regulations in timber buildings.

All others were discussed by Cheng et al. (2022).

10. Conclusions

Fire safety is a great concern when using timber as construction materials for achieving a sustainable environment. As presented above, though the fire behavior of timber products has been well researched, fire behavior and rescue strategy are expected to be very different for timber buildings as compared with low-rise timber buildings. Training of professionals (including engineers and fire safety personnel) and formulation of regulations, codes and guidelines are the final guards to ensure a safe timber building. In addition, education and promotion among the general public of the fire safety of timber buildings is an important step to remove obstacles arising from ungrounded fear.

If these concerns have been adequately addressed, there is no reason to refrain from the construction of timber buildings, even high-rise timber buildings.

Declaration of Interests

None.

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Timber Building Fire Safety 2023-1d

Table 1: List of multi-story timber buildings proposed

Building Name	Stories	City, Country	Status
Oakwood Tower	80	London, United Kingdom	under research
W350 project	70	Tokyo, Japan	planned
Timber Towers	60	Philadelphia, United States	under research
The Spar	48	Portland, United States	proposed
Tratoppen	40	Stockholm, Sweden	proposed
Baobab	35	Paris, France	proposed
Abebe Court Tower	26	Lagos, Nigeria	proposed
HoHo Wien	24	Vienna, Austria	proposed
Michael Green	20	Vancouver, Canada	proposed
Terrace House	19	Vancouver, Canada	under construction
Silva	18	Bordeaux, France	proposed
Tree Tower	18	Toronto, Canada	proposed
Wood’Up	18	Paris, France	planned

Source: Tall timber: A Global Audit, CTBUH Journal No. 2 (2017) 47-49, and others

Table 2: Summary of some recent reports on full-scale fire tests of timber buildings

Literature	Size of Compartment or fire room	Location	Material/ Structure	Types of Fuel/ Fire Source	Provision of Sprinkler	Major findings/Observations
Hakkarain et al. (2002)	3.5 m × 4.5 m × 2.5 m, Opening: 2.3 m × 1.2 m	Finland	Heavy Laminated Timber	Wood Crib	No	One protective layer of gypsum plasterboard can delay the onset of charring by 20 min.
Stein & Winter (2008)	4.5 m × 4.5 m × 2.5 m	Munich, Germany	One-story timber building with cellar and attic	Fire load density of 619 MJ/m^2	No	Fire occurred in living roon and spread to roof through window with 12 min
Peng et al. (2011)	5.7 m x 3.0 m x 4.5 m; Door 0.9 m x 2.0 m' With or without ceiling	Lijiang, China	Timber	Raw wood or common furniture	Yes/No	Sprinkler system is important in preventing fire spread. Spread is easier if fire occurs near wooden wall. Burning of materials like foam mattress causes rapid spread of fire.
Hasemi et al. (2014)	3-story school building	Waseda University ,Japan	Timber	Wood crib	No	Upward spread of fire through window was observed. Fire also spread through fire door of fire wall. Fire wall collapsed eventually. Effectiveness of fire wall and ceiling is important in preventing fire spread.
Kolaitis et al. (2014)	2.22 m x 2.22 m x 2.11 m; Window 0.430 m x 0.98 m	Greece	Timber frame for 2 walls and ceiling, CLT for 2 walls and floor	Wood crib 0.9 m x 1.2 m x 0.66 m is placed at the NE corner of the	No	Gypsum plasterboards offer better fire protection than wood based panels.
Su & Lougheed (2014)	8.5 m x 4.4 m x 2.4 m.	Quebec, Canada	Cross-laminated timber (CLT) and lightweight (cold-formed) steel frame (LSF)	Typical furniture and contents in residential occupancies/ ignition of bedding	No	Different wall assemblies were tested to obtain the time to structural failure in case of fire.
Li et al. (2016)	3.5 m × 4.5 m × 2 m, Door: 1.1 m × 2 m	Canada	CLT unprotected, CLT protected, CLT partially protected, Light Timber /steel frame	Furniture	No	Unprotected CLT became part of the combustible contents, responsible for over 60% of the total heat release. For Protected CLT, the HRR was half that for unprotected CLT.
Tian et al. (2016)	4 m x 3 m x 2.6 m (height)	Kunming, China	Timber	Wood crib, each bar of 0.6 m x 0.035 m x0.025 m, with a clearance ratio of 1:2, in 10 layers.	No	Max. heat release rate = 9 MW. Max. temperature of fully developed fire 700 ^{0}C
Hoehler et al. (2018)	9.1 m × 4.6 m × 2.7 m,	USA	CLT, fully or partially lined with gypsum board	Residential contents and furnishings, fuel load density of 550 MJ/m^2	No	Ventilation conditions had significant effect on fire development. The exposed area of CLT contributed to fire intensity. To minimize delamination heat-resistant adhesives in CLT should be used.
Zelinka et. al (2018)	Two-story timber building. Dimensions of each apartment : 9.14 m × 9.14 m × 2.74 m,	Maryland, USA	CLT, with surface area protected by gypsum wallboard ranging from 100% to no protection	Furniture and wood cribs	Yes/No	Three variables were studied: amount and location of exposed mass timber surface, opening in wall, and effect of sprinkler system

Table 3: Summary of computer simulation studies on fire and fire spread in timber buildings

Reported studies	Material/Structure	Software/Modelling method	Objectives
Tsujihara et al. (2004)	Building group with wooden houses	Self-developed simulation system	Fire spread after earthquake
Hietaniemi and Mikkola (2010)	wooden cribs	FDS	HRR and growth of fire in room fire
Himoto and Tanaka (2010)	Area consisting mostly of wood-frame structures	Monte Carlo Method	Fire spread in densely populated urban area
Werther et al. (2014)	timber column/strip	ANSYS, SAFIR, ABAQUS	Comparison of different finite element software
Tian et al. (2016)	wooden cribs	Statistics, Monte Carlo method, FDS, finite element method	Pyrolysis temperature and reaction heat of timber
Ek and Anderson (2017)	timber assemblies	TASEF	Temperature distribution and charring depth
Zeng et al. (2017).	Rural areas which were mostly wooden buildings	Simulation with visualization based on OSG	Fire spread in rural areas in South-western China
Dârmon and Suciu (2018)	timber building	FDS	Smoke ventilation
Dembsey et al. (2018)	timber building	FDS, RISA, PATHFINDER	Effect of sprinklers
Kmiecik (2018)	glue-laminated timber beam	FDS, SAFIR	Time varying spatial map of temperature
Thi et al. (2018)	gypsum plaster board, gypsum-faced CLT	ABAQUS, UMATHI	Fire integrity resistance