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Su, Joseph

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FIRE SAFETY OF CLT BUILDINGS IN CANADA

*Joseph Z. Su**
National Research Council Canada
Ottawa, Canada
E-mail: joseph.su@nrc-cnrc.gc.ca

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Abstract. This article provides an overview of the code requirements pertinent to large cross-laminated timber (CLT) buildings and the methods for meeting the requirements in Canada. Canadian building codes are objective-based. Compliance with the code is achieved by directly applying the acceptable solutions up to certain prescriptive building sizes (height and area) or by developing alternative solutions beyond the height and area limits. The fire safety design for a CLT building larger than the prescriptive limit must demonstrate that the building will achieve at least the minimum level of performance afforded by noncombustible construction in limiting the structural involvement in fire and contribution to the growth and spread of fire during the time required for occupant evacuation and emergency responses.

Keywords: Cross-laminated timber, building fire safety and protection, fire resistance, performance based design, alternative solution.

INTRODUCTION

Designers and developers in Canada and around the world are expanding the use of mass timber structures, such as structures comprising cross-laminated timber (CLT), in increasingly higher and larger buildings for sustainable development to reduce energy consumption and carbon footprint. Several tall wood buildings using mass timber as structural systems, including CLT manufactured in conformance with ANSI/APA PRG 320 (APA 2012), have been constructed in Canada, such as Brock Commons in Vancouver (Forestry Innovation Investment (FII) 2018), Origine in Québec City (Nordic Structures (NS) 2018b), and Arbora in Montreal (Nordic Structures (NS) 2018a). Technical guides are available to practitioners for designing tall wood buildings to meet the Code requirements (Dagenais 2014; Harmsworth et al 2014).

CANADA'S BUILDING REGULATIONS

The National Building Code (NBC) of Canada (NRC 2015a) is a model construction code that is adopted in its entirety, or adapted for regional variances, by the individual provinces and territories who have jurisdiction over building regulations. The NBC provides minimum requirements for safety, health, accessibility, fire, and structural protection in the design and construction of new buildings. It also applies to the substantial renovation and the demolition or relocation of existing buildings. The NBC is an objective-based code with clearly stated objectives and functional statements for its requirements. Compliance with the code is achieved by directly applying the acceptable solutions (ie prescriptive requirements in Division B of the code) or by developing alternative solutions.

ACCEPTABLE SOLUTIONS

Buildings designed using the acceptable solutions are automatically deemed to satisfy the objectives and functional statements of the code. The prescriptive construction requirements for fire safety and protection of buildings are dependent on the building size and occupancy type. Under the current acceptable solutions of the NBC 2015, all buildings are categorized into two types: combustible construction and noncombustible construction. As timber buildings are categorized as combustible construction, they are restricted to a maximum of six storys in building height for residential, business, and personal services occupancies and required to be sprinklered throughout. The maximum building areas of the

* Corresponding author

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six-story timber buildings are 1500 m^2 (per story) for residential occupancies and 3000 m^2 (per story) for business and personal service occupancies, respectively. The allowed height and area for timber buildings for other occupancies are further reduced (timber buildings for detention occupancies are not allowed). Because the NBC is revised every 5 yr, new limits for the height and area may be introduced in the 2020 edition.

For buildings that exceed the height and area limits for combustible construction, the prescriptive provisions (acceptable solutions) require that the primary structural elements be of noncombustible construction. The intent of the prescriptive requirements for noncombustible construction, as they relate to the NBC objectives for fire safety and building fire protection, is:

> *to limit the probability that combustible construction materials within a storey of a building will* ***be involved*** *in a fire, which could* ***lead to the growth*** *of fire, which could* ***lead to the spread*** *of fire within the storey* ***during the time*** *required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to persons and damage to the building (NRC 2012).*

DEVELOPMENT OF ALTERNATIVE SOLUTIONS

When designers and builders want to use timber as the structural elements in a building that is higher and/or larger than the applicable prescriptive height and area limit, they must develop a building design along with an alternative solution proposal for approval by the authority having jurisdiction (AHJ). They must clearly demonstrate to the AHJ that their proposed alternative solutions meet the minimum level of performance in the areas defined by the objectives and functional statements attributed to the applicable acceptable solutions. In other words, designers and developers must demonstrate that proposed mass timber buildings perform at least as well as noncombustible construction in the areas defined by the applicable objectives and functional statements.

The alternative solutions can be developed and assessed in various approaches, including full fire-risk assessment against benchmark performance. Although a performance-based design approach can be applied, a practical approach used so far is to design the large timber buildings that meet all applicable requirements prescribed for noncombustible construction except employing mass timber as the structural elements. This simplifies to demonstrating that the proposed building will achieve the minimum level of performance afforded by noncombustible construction in limiting the involvement and contribution of structural elements to the growth and spread of fire for an acceptable duration.

Encapsulation of Mass Timber Structural Elements

Encapsulation of mass timber structural elements can be used as an alternative solution for tall wood buildings to meet the code objectives and functional statements pertinent to the requirements of noncombustible construction. The principle, successfully used in Europe, is to keep the timber surface below its charring temperature (approximately 300°C) for a period of time (Östman et al 2010). Encapsulation materials (such as gypsum board, cement board, and gypsum–concrete, etc.) can be used as a protective cover to protect the mass timber structural elements for a period of time to delay the effects of the fire on the timber structural elements, including delay or even avoidance of ignition. In delaying ignition, any effects of the combustion of the structural elements on the fire severity and spread can be delayed or even reduced if the fire reaches the decay stage. The objective of encapsulation is to limit the probability that the mass timber elements significantly contribute to fire spread and fire duration in the event of a fire.

Full Encapsulation

A considerable amount of performance data on fully encapsulated CLT structure systems is available from small- to large-scale fire tests under standard and nonstandard fire exposure conditions (McGregor 2013; Berzins et al 2014; Bijloos et al 2014; Su and Lougheed 2014;

Su et al 2014b; Taber et al 2014; Janssens 2015; Su and Muradori 2015; Hasburgh et al 2018; Su et al 2018). The large-scale tests demonstrated that encapsulating the CLT compartments using physical barriers was an effective means to delay and/or prevent the ignition and involvement of the timber structural elements in fires, limiting and/or eliminating their contribution to the fires. The data can be used to develop alternative solutions.

To provide a path for designers and builders who wish to obtain approval of timber buildings up to 12 storys, the provincial government of Quebec has established an expedited alternative solution process and published a guide (Régie du bâtiment du Québec (RBQ) 2015). If designed and built in compliance with the conditions stipulated in this guide, such buildings are deemed to comply with the code requirements in Quebec, without requiring an application for an alternative solution. These buildings are intended for Group C (residential) or Group D (business and personal services) occupancies, or a combination of the two.

Partial Encapsulation and Issues of Exposed CLT

Partially encapsulated, ie partially exposed, CLT structures must also achieve the minimum level of performance afforded by noncombustible construction in limiting the structural involvement in fire and contributions to the growth and spread of fire for an acceptable duration. Performance data on exposed CLT structures are available from compartment fire tests (McGregor 2013; Medina Hevia 2014; Janssens 2017; Hasburgh et al 2018; Su et al 2018). CLT contributions to the compartment fires are dependent on the amount and orientation of the CLT surfaces exposed and involved in the fires, delamination behaviors of CLT involved, and ventilation conditions among others. The experimental results have highlighted several areas to be addressed in developing the alternative solutions for fire safety designs.

Amount and orientation of exposed CLT surface area. Exposed CLT panels add fuel to compartment fires. The amount and orientation of exposed CLT surfaces have an impact on the CLT contribution to compartment fires. For the CLT exhibiting delamination behavior before the bond line reaches the charring temperature, the exposed CLT surfaces contributed to compartment fires to an extent from delayed fire decay, to second flashover or regrowth at delamination events, to no fire decay (Su et al 2018). To limit the probability that the exposed CLT elements significantly contribute to fire duration and spread, the orientation and area of exposed surfaces within a suite should be determined to restrict reradiation to each other and too large an exposed area that could sustain combustion and regrow.

Ventilation and exposed CLT surface area. Ventilation conditions have a large impact on compartment fires and, thus, CLT contribution to the fires. In the experiments by Su et al (2018), the ventilation effect was clearly demonstrated with two different opening sizes. In the compartment tests with a relatively small opening for ventilation, the exposed CLT elements experienced a longer duration of fully developed fire, delaminated earlier, and became more involved in the fire. The area of exposed CLT surfaces should be determined in consideration of potential ventilation conditions to limit the CLT contribution to a fire.

Delamination and adhesives. Delamination was observed in several CLT compartment tests with exposed CLT panels (Janssens 2017; Su et al 2018), causing fire regrowth. This has become an important issue for fire safety design for CLT construction. Model-scale horizontal furnace tests (Klippel et al 2017; Brandon and Dagenais 2018) and compartment tests (Janssens 2017) were conducted recently using CLT with different types of adhesive. A couple of adhesives have shown improved fire performance in preventing premature fall-off of charred CLT ply pieces. The newly revised North American CLT qualification standard ANSI/APA PRG 320 requires that the adhesives used in CLT be evaluated for elevated temperature performance in a room-scale fire test with an unprotected CLT floor–ceiling assembly (APA 2018). This will screen out the products that result in premature fall-off of charred CLT layers and fire regrowth. The use of improved adhesives in CLT products will minimize delamination in case of fire and, therefore, resolve the issues of delamination-caused fire regrowth with exposed CLT.

Flame spread rating. For the wall, ceiling, and floor surfaces of exits, exit stairways, and vestibules to exit stairs, the code requires that the flame-spread rating be no more than 25 and smoke developed classification no more than 50, based on CAN/ULC-S102 "Test for Surface Burning Characteristics of Building Materials and Assemblies" (ULC 2010a). The requirement intends to limit the spread of fire across the exposed surfaces. Exposed CLT would be inappropriate for these locations unless special wood treatments and protection measures are demonstrated to be effective.

Fire blocks in concealed spaces. The code requires fire blocks in certain concealed spaces to limit the probability that fire will spread to or through other concealed spaces or other parts of the building. Installation of sprinklers or noncombustible insulation in horizontal concealed spaces within a floor assembly or roof assembly can also meet the requirement for fire blocking.

Agreement on Review and Approval Process

Generally, there are no harmonized approaches to develop and assess alternative solutions. Designers and developers are advised to meet with the local AHJ at the early stage to agree on the path forward and appraisal process (third-party or peer reviewers), and also interact with the AHJ and review panel throughout the process. This is particularly important in the areas where the minimum level of performance is implicit and where fire testing may be required to compare the performance of a proposed design with the noncombustible benchmark.

OTHER KEY REQUIREMENTS FOR FIRE SAFETY AND PROTECTION

As mentioned earlier to facilitate approval, tall and large timber buildings so far are designed to meet all other applicable requirements prescribed for noncombustible construction. These requirements include, but are not limited to, sprinklers, fire resistance, penetrations in fire separations and fire-rated assemblies, high buildings, exterior fire spread, etc.

Automatic Sprinkler Systems

For a building of more than six storys in building height, an automatic sprinkler system designed, constructed, installed, and tested in conformance with NFPA 13 (NFPA 2013) is required throughout the building along with fire alarm systems. The intents are to limit the probability of the growth of fire at fire origin, of the spread of fire within the storey, and of the spread of fire from a lower story to an upper story or to the exterior of a building during the time required to achieve occupant safety and for emergency responders to perform their duties. Depending on major occupancies of the buildings, this requirement starts to apply at different building heights. But regardless of major occupancies, this requirement applies to all buildings that are more than six storys in building height.

Fire Resistance of CLT Assemblies

In all buildings of more than six storys in building height, the prescriptive provisions of NBC 2015 require that the floor assemblies be fire separations with a fire-resistance rating not less than 2 h. The loadbearing walls, columns, and arches are required to have a fire-resistance rating not less than that required for the supported assembly. The intents are to limit the probability of premature failure or collapse of the structural and separating elements when exposed to fire, which could lead to the spread of fire from a lower story to an upper story or to the exterior of the building during the time required to achieve occupant safety and for emergency responders to perform their duties.

The fire-resistance rating of a material, an assembly or a structural element must be determined based on the results of tests conducted in conformance with CAN/ULC-S101, "Standard Method of Fire Endurance Tests of Building Construction and Materials" (ULC 2014). The fire-resistance rating is assigned based on the fire endurance period over which criteria for insulation, integrity, and structural resistance performance are met by the test assembly. The fire endurance period of a floor/wall assembly is defined by the period over which the assembly sustains the applied load without passage of flames or gases hot enough to ignite cotton pads; the average temperature measured on the unexposed side of the assembly does not exceed 140°C more than the initial average temperature; and no individual temperature measured on the unexposed side of the assembly exceeds 180°C more than the initial temperature.

Fire-resistance ratings of CLT assemblies based on the CAN/ULC-S101 tests are available (Osborne et al 2012; Dagenais 2014; Su et al 2014a; Su 2016). Fire-resistance ratings developed in accordance with similar standard test methods, such as ASTM E119 (ASTM 2016) and ISO 834 (ISO 1999), are usually acceptable to Canadian building officials depending on their familiarity with these standards.

Where the fire-resistance ratings based on the standard tests are not available, alternative engineering methods may be used. Annex B of CSA O86-14 (CSA 2014) provides an engineering method to predict fire-resistance ratings of CLT based on the structural criteria. The reduced cross-section after deduction of the char depth and the zero-strength layer (7 mm) from each exposed surface is used to predict fire-resistance performance of CLT for loadbearing. The char depth for the CLT is calculated using the one-dimensional charring rate of 0.65 mm/min if the char depth will not reach the first bond line during the fire-resistance period required. The notional charring rate of 0.80 mm/min is used if the char depth will surpass the first bond line during the fire-resistance period required. This method only addresses the structural fire resistance for supporting the applied load for the duration of the fire resistance required, not the fire separation function (insulation and integrity) of the building elements. CLT Handbook (Dagenais 2014) describes an alternative methodology to predict fire-resistance performance of CLT addressing each of the three criteria for insulation, integrity, and structural resistance performance, which provides conservative predictions compared with available experimental results.

Connections. Connections withstanding gravity loads on the structure are required to have a fire-resistance rating not less than that required for the supported elements. Such connections should be concealed within the reduced cross-section of CLT elements or protected against exposure to fire.

Penetrations in Fire Separations and Fire-Rated Assemblies

Penetrations of a fire separation or a fire-resistance rated assembly must be sealed by a firestop to limit the potential integrity failure of the fire separation and premature collapse or failure of the fire-rated assembly. The firestop acts as a barrier to the spread of smoke and fire and is rated using CAN/ULC-S115 test method, "Fire Tests of Firestop Systems" (ULC 2011). Most of the fire separations and fire-rated assemblies that are required to have a 2-h fire-resistance rating must have a firestop with an F rating not less than 1.5 h to seal the penetrations. A significant amount of firestop tests for CLT assemblies are documented by Harmsworth (2016).

High Buildings

Certain buildings of residential occupancies, buildings containing care and treatment occupancies, and buildings of assembly, business and personal services, mercantile, and industrial occupancies with an occupant load exceeding 300, are considered high buildings in which the floor level of the top story is more than 18 m above grade. High building requirements are therefore triggered at this height. Among all the requirements, a high building is required to be designed so that, during a period of 2 h after the start of a fire, each exit stair serving storys below the lowest exit level will not contain more than 1% by volume of contaminated air from the fire floor. This usually can be achieved by pressurizing the exit stair to 12 Pa. The intent of this requirement is to limit the danger to occupants and firefighters from exposure to smoke in a building fire.

Limiting Exterior Fire Spread

CLT exterior wall cladding with limiting fire spread. For CLT to be used in an exterior wall assembly in a sprinklered tall wood building, the wall assembly must satisfy acceptance criteria when tested in accordance with CAN/ULC-S134, "Fire Test of Exterior Wall Assemblies" (ULC 2013), for limiting fire spread on or within the exterior wall assembly. This test method evaluates the performance of an exterior wall assembly under controlled conditions representing the fire exposure resulting from a post flashover fire in a compartment venting through an opening in the wall. The test evaluates fire spread over the exterior surface, heat flow from the fire plume to the exterior surface, and fire spread within the test assembly. The acceptance criteria are: 1) no more than 5 m of vertical flame spread and 2) no more than 35 kW/m^2 heat flux on the wall assembly measured at 3.5 m above the vent opening. Several CLT exterior wall assemblies were tested in accordance with CAN/ULC-S134 standard fire test (Gibbs et al 2014; Gibbs and Su 2015), meeting the code requirements in limiting the fire spread and heat flow.

Roof coverings. Roof coverings on timber buildings are required to have a Class A classification where the roof height is greater than 25 m from the floor of the first story. The roof covering classification is determined in conformance with CAN/ULC-S107, "Fire Tests of Roof Coverings" (ULC 2010b).

FIRE SAFETY AT CONSTRUCTION SITES

Fire safety at construction sites must conform to Section 5.6 of Division B of the National Fire Code (NFC) of Canada 2015 (NRC 2015b). In addition to the NFC requirements, best practices to enhance fire safety at construction sites include maintaining clearance from combustible waste, limiting the area of unprotected CLT surfaces, and putting in place an operable standpipe system during construction.

In addition to maintaining a clearance of not less than 3 m between exits and containers used for the disposal of combustible refuse as required, the same clearance is advisable between the containers and any portion of the building under construction. A temporary standpipe system can be installed or a permanent standpipe system can be progressively installed and kept in operable conditions at all times. The area of exposed CLT can be limited by installing protective materials, such as gypsum boards, etc., on the floor and wall assemblies to a certain extent on each story or by exposing at any time no more than four upper contiguous storys. The protective measure aims to limit the potential for fire spread within the story, and limit the potential for fire spread to upper storys and, thereby, limit the potential exposure of adjacent structures in a fire situation.

CONCLUSIONS

Designers and developers in Canada and around the world are expanding the use of mass timber structures in increasingly higher and larger buildings. Several tall wood buildings have been constructed in Canada using CLT and other mass timber elements as structural systems. An overview of the Canadian code requirements pertinent to large CLT buildings and the methods for meeting the requirements is presented in this article. Compliance with the objective-based code can be achieved by developing alternative solutions for tall wood buildings. The fire safety design for a large CLT building must demonstrate that the building will achieve at least the minimum level of performance afforded by noncombustible construction in limiting the structural involvement in fire and contribution to the growth and spread of fire during the time required for occupant evacuation and emergency responses. Technical guides are available to practitioners for designing tall wood buildings to meet the code requirements.

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