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REVIEW OF THE CODE DEVELOPMENT EFFORTS FOR TALL MASS TIMBER BUILDINGS IN THE US

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ABSTRACT: The 2021 International Building Code (IBC) is the current edition of the predominant model building code adopted for use in the United States. For the first time in the history of US model code development, the 2021 IBC recognizes tall mass timber buildings. With the addition of three new types of construction, US designers can design tall mass timber structures up to 18 stories in height. These provisions are the culmination of a nearly five-year effort by stakeholders participating in the code development process. A brief history of this effort is presented in this paper, including the formation of the International Code Council's (ICC) Tall Wood Ad Hoc Committee. Four (4) work groups, namely, Definitions and Standards, Fire, Structural, and Codes were convened to formulate science-based code change language that led to the current provisions. Analysis of the fire testing completed in support of the code changes is presented and a brief discussion of current research and testing, as well as proposed code changes for future editions of the IBC is also discussed.

KEYWORDS: Cross-laminated Timber, Building Codes, Tall Mass Timber

1 INTRODUCTION

1.1 IBC/IRC

Structural building design in the United States most commonly falls under the jurisdiction of one of two model codes developed by the International Code Council (ICC): the International Residential Code® (IRC®) or the International Building Code®(IBC®). The IRC addresses the design and construction of one- and two-family dwellings and townhouses not more than three stories above grade. The IBC is applicable to all buildings, apart from structures designed to meet the requirements of the IRC. States or other localities across the US regularly adopt updated versions of these standards as their building code – sometimes without alterations, other times with deletions or amendments as the locality deems necessary. The process of code adoption varies from state to state, as evidenced by the map in Figure 1. Some states use a statewide adoption process, while others allow local authorities to adopt updated codes at their discretion. The IBC and IRC both have top-to-bottom provisions for the design and construction of buildings of various structural materials and systems. This paper focuses on the IBC provisions related to structural design and fire safety for mass timber structures.

1.2 NDS/SDPWS

Within the IBC and IRC are dozens of referenced standards produced by relevant organizations. The referenced standard for structural design of wood buildings is the *National Design Specification®* (NDS) *for Wood Construction*. Lateral force resisting systems in wood structures subject to wind or seismic loads are governed by the provisions of the *Special Design Provisions for Wind and Seismic®* (SDPWS), also a referenced standard in the IBC and IRC. Both the NDS and SDPWS are published by the American Wood Council (AWC), a not-for-profit trade association representing North American wood products manufacturers. AWC is accredited by the American National Standards Institute (ANSI) and develops state-of-the-art engineering data, technology, and standards on structural wood products for use by design professionals and building officials.

The NDS is AWC's longest tenured standard, providing structural and fire design provisions for solid sawn and engineered wood products as well as connections in these wood products. In the 2015 edition [1] of the NDS, structural and fire design provisions for cross-laminated timber (CLT) were added. Codified lateral design provisions for CLT diaphragm and CLT shear wall systems were subsequently introduced in the 2021 edition of SDPWS [2].

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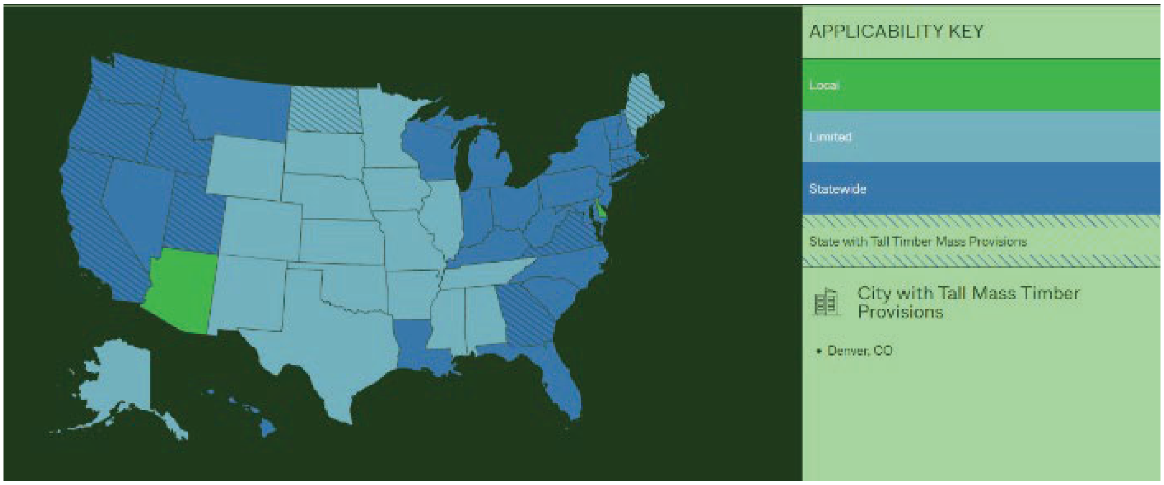

Figure 1. *Code Adoption Map*

2 WOOD BUILDING CODES PRIOR TO 2015

Type IV-HT Heavy Timber construction (referred to as Type IV prior to the adoption of the 2021 IBC [3] Tall Mass Timber provisions) have been present not only through the entire history of the IBC, but also in the historic "legacy" codes used prior to 2000 throughout the US. The definition of Type IV-HT is as follows: "*Type IV construction (Heavy Timber, HT) is that type of construction in which the exterior walls are of noncombustible materials and the interior building elements are of solid wood or laminated wood without concealed spaces…Minimum solid sawn dimensions are required for structures built using Type IV construction (HT)…"* [4].

The story and height limits for Type IV-HT - Heavy Timber construction under the 2015 IBC [4] (and previous editions) is 6 stories and 26m (85 ft) height. Buildings classified as Type IV construction have non-combustible exteriors, and the timber primary structural frame is required to meet minimum dimensional criteria (nominal 6" x 8"/153mm x 203mm for columns and nominal 6" x 10"/153mm x 254mm for beams or joists).

In historic heavy timber buildings (Figure 2a), the robust cross sections of the members stand in stark contrast to the smaller members used in conventional repetitive light-frame wood construction (Figure 2b). Repetitive light-frame buildings in the US can refer to both Type III or Type V construction. Type III construction is defined in the IBC as follows: "*Type III construction is that type of construction in which the exterior walls are of non-combustible materials and the interior building elements are of any materials permitted by this code. Fire-retardant treated wood framing and sheathing complying with Section 2303.2 shall be permitted within exterior wall assemblies of a 2-hour rating or less."* Type V construction is defined as: *Type V construction is that type of construction in which the structural elements, exterior walls and interior walls are of any materials permitted by this code* [4].

In some instances, Type III-A can match the building height of Type IV-HT buildings (85' feet/26m) but may permit fewer stories due to occupancy type restrictions and sprinkler system configurations. Additionally, until all the passive and active fire protection and fire-resistance rated construction is complete, repetitive light frame buildings are typically more susceptible to threats from fire than Type IV-HT structures. The inherent structural mass of Heavy Timber imparts fire resistance to the primary structural frame because of the ability of wood to slowly char over time, versus sudden catastrophic structural collapse of other construction materials that are exposed to fire.

The term *cross-laminated timber* appears for the first time in the US codes in the 2015 edition of the IBC [4]. It is defined therein as: *a prefabricated engineered wood product consisting of not less than three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross oriented and bonded with structural adhesive to form a solid wood element*. The manufacturing standard for cross-laminated timber, ANSI/APA PRG-320 [5] also makes its first appearance in the 2015 IBC. This permitted the use of CLT as a building element in Type III, IV and V construction. These two changes in the 2015 IBC were instrumental towards the eventual adoption of Tall Mass Timber/Tall Wood Building changes in the 2021 IBC [3].

Following the definition of cross-laminated timber and the manufacturing standard in the 2015 IBC, changes to the 2018 IBC were more intended as a reorganization of terms, content, and referenced standards associated with wood construction. Content describing Heavy Timber that was originally contained within Chapter 6 (Types of Construction) was relocated to Chapter 23 (Wood chapter). Chapter 23 received many new entries specific to cross-laminated timber. A Table was created to call out dimensions for heavy timber structural components comprised of solid sawn lumber, structural glued laminated timber (Glulam), and structural composite lumber (SCL) for column, floor, beam, girder, and roof framing members. Prior to the adoption of the 2021 IBC terms like *mass timber* and *tall mass timber* were not defined.

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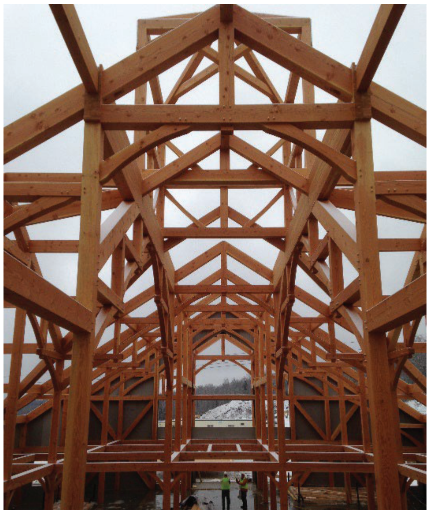

(a)

(b)

Figure 2. *(a) Traditional Heavy Timber, Type IV-HT, (b) a repetitive light-frame podium building*

3 ICC TALL WOOD BUILDING AD-HOC COMMITTEE

In late December of 2015, industry members and other interested parties petitioned the ICC to explore the science of tall wood buildings and take action to develop the necessary code changes to support this new construction type. The ICC determined this effort was valid and formed an Ad-Hoc Committee to evaluate the potential for new mass timber construction types in the IBC. The Tall Wood Building Ad-Hoc Committee, or TWBAH as it became known, was formed under the leadership of ICC [6]. Over eighty individuals volunteered to serve on the TWBAH, and this consensus-based committee was comprised of representatives from building material industries (including members from concrete, steel, and masonry industries), respected building and fire officials, registered professional architects and structural engineers, fire protection experts, and other industry related stakeholders.

Due to the tremendous volume of data that required review, the TWBAH appointed four work groups: Definitions and Standards, Fire, Structural, and Codes. These work groups immediately identified several key performance objectives that guided their development of any proposed code changes:

- No collapse under reasonable scenarios of complete burn-out of fuel without automatic sprinkler protection being considered.
- No unusually high radiation exposure from the subject building to adjoining properties to present a risk of ignition under reasonably severe fire scenarios.
- No unusual response from typical radiation exposure from adjacent properties to present a risk of ignition of the subject building under reasonably severe fire scenarios.
- No unusual fire department access issues.
- Egress systems designed to protect building occupants during design escape time, plus a factor of safety.
- Highly reliable fire suppression systems to reduce risk of failure during reasonably expected fire. Degree of reliability proportional to evacuation time (height) and risk of collapse.

The TWBAH worked for almost 5 years to analyze data and research from across the globe on CLT and mass timber buildings. The Fire Work group had arguably the most challenging task of identifying realistic fire test scenarios to validate the increased story and overall heights proposed by the TWBAH. Fortunately, several notable fire tests of cross-laminated timber had been conducted prior to the formation of the committee [7]. In 2012, an ASTM E119 [8] test was conducted on a 5-ply CLT wall panel assembly that was loaded with 87,000 pounds (39,462 kg). The intent of the test was to have the assembly obtain a two-hour fire-resistance rating. The test was concluded when flame front penetration was observed through the assembly at three-hours and six minutes.

Additional compartment fire testing was conducted at the Southwest Research Institute (SWRI) in 2015 [9], the research and fire test labs at NIST (National Institute of Science and Technology) in the National Research Council of Canada in 2017[10]. Follow-up testing of heat resistant adhesives to ensure the layers of CLT did not delaminate during fire conditions were also conducted at SWRI in 2017 [11]. All the data from previous fire tests was taken into consideration to design the fire tests that were conducted on the two-story test structure at the US ATF (Bureau of Alcohol, Tobacco, Firearms and Explosives) laboratory in direct support of the proposed Tall Mass Timber code change proposals in the 2021 IBC.

The five fire test scenarios conducted at ATF [7, 12] are described in Table 1.

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Table 1: Summary of ATF Fire Tests

Test	Description	Date	Duration
1	All mass timber surfaces protected with 2-layers of 15.9 mm (5/8 in.) Type X GWB – establishes baseline	5/23/17	3 hours
2	30% of CLT ceiling area in living room and bedroom exposed – represents maximum exposure in Type IV-B	5/31/17	4 hours
3	Two opposing CLT walls exposed – one in bedroom and one in living room (there is a partition wall) – Type IV-B	6/20/17	4 hours
4	All mass timber surfaces fully exposed in bedroom and living room. Sprinklered – normal activation	6/27/17	6 minutes
5	All mass timber surfaces fully exposed in bedroom and living room (except bathroom). Sprinklered – 23 min delayed activation	6/29/17	30 minutes

Figure 3: *Fire Test 1 test progression photos*

All the fire tests conducted at the ATF laboratory were designed to replicate the actual conditions as permitted under the proposed Tall Mass Timber code change proposals. These fire tests validated the fire performance of CLT and the ability of the material to withstand flame and sustained high temperatures (over 1000°C and 18 and 23 megawatts of energy release) generated by the room and contents fire without any contribution of the fire sprinkler system.

It should be noted that the CLT panels tested at the ATF were not manufactured with adhesives that are required under the most current CLT manufacturing standard, ANSI/APA PRG320-18 [5]. The use of fire-resistant adhesives only increased the robust fire performance of CLT as proven in follow on testing conducted at the Research Institute of Sweden (RISE) in 2020 [13].

A total of five additional compartment tests were conducted at RISE [13], all with the primary objective of exposing increasing amounts of exposed CLT ceiling surfaces. A secondary objective was to model the performance of exposed ceiling and wall intersections.

The robust fire resistance of CLT panels manufactured in accordance with ANSI/APA PRG 320-18 [5] was again validated during the RISE tests. The testing proved that CLT constructed with heat-resistant adhesives did not lead to fire regrowth conditions or result in elevated ceiling temperatures greater that 600°C after the decay phase.

4 CLT SHEAR WALL DESIGN REQUIREMENTS

Seismic design based on the equivalent lateral force procedure in the IBC relies on factors from referenced standard ASCE/SEI 7 – *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [14]. The design requirements are provided in ANSI/AWC *Special Design Provisions for Wind and Seismic* 2021 edition (SDPWS-21) [2]. The SDPWS-21 is referenced in the 2021 IBC [3], and both SDPWS-21 and ASCE 7-22 will be referenced in the 2024 IBC.

The two defined CLT shear wall system types in SDPWS-21 are: (a) *CLT shear wall system* and (b) *CLT shear wall system with shear resistance provided by high aspect ratio panels only*. Both have seismic design factors (i.e., R, Ω_0, C_d) provided in ASCE 7-22 Table 12.2-1. Seismic performance factors and structural height limits appearing in ASCE 7-22 are summarized in Table 2.

Individual CLT panels of CLT shear walls are expected to exhibit rocking, as shown in Figure 4, with the strength of the system controlled by nailed connections. Typical CLT shear wall configurations with the corresponding components are shown in Figure 5. Prescribed nailed connectors are shown at the bottoms and tops of panels and at adjoining vertical panel edges. For multi-panel configurations, free-body diagrams for the tension end panel and compression end panels are shown in Figure 6. To ensure rocking behavior, as shown in Figure 4, and development of the nailed connection strength, design requirements include: (1) use of CLT panels of prescribed aspect ratios; (2) use of prescribed nailed connectors at bottoms of panels, tops of panels, and adjoining vertical edge(s) of multi-panel shear walls; (3) strength requirements for overturning tension devices (e.g., hold-downs); and (4) compression zone length requirements. Design requirements also include equations for calculating nominal unit shear capacity provided by the prescribed nailed connectors and for calculating the CLT shear wall deflection. The structural design of the CLT panels for resistance to tension, compression, bending, and shear, as well as the design of connections to CLT panels, is required to be in accordance with the NDS. Requirements for the design of CLT diaphragms are also provided in SDPWS.

Table 2: *Design Coefficients and Factors for CLT Seismic Force-Resisting Systems (appearing in ASCE/SEI 7-22 Table 12.2-1)*

Seismic Force-Resisting System	Detailing Requirements, ASCE/SEI 7-22 Section	R	Ω_0	C_d	Structural Height, h_n, Limit Seismic Design Category B, C, D, E & F
Cross-laminated timber shear walls	14.5	3	3	3	20 m [65 ft]
Cross-laminated timber shear walls with shear resistance provided by high aspect ratio panels only	14.5	4	3	4	20 m [65 ft]

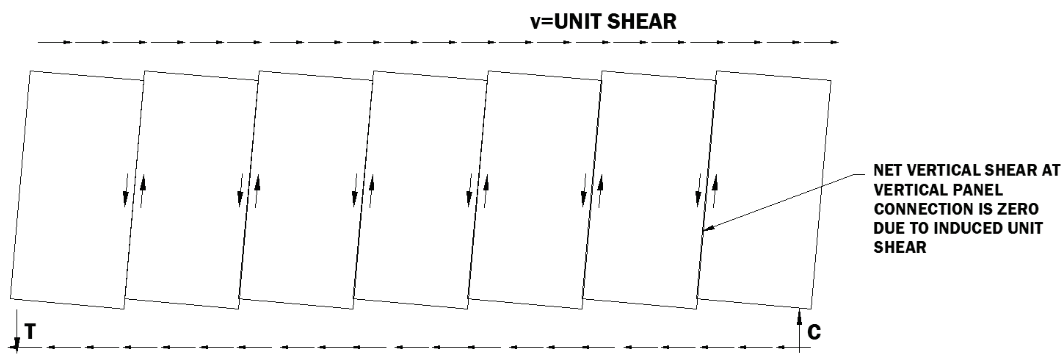
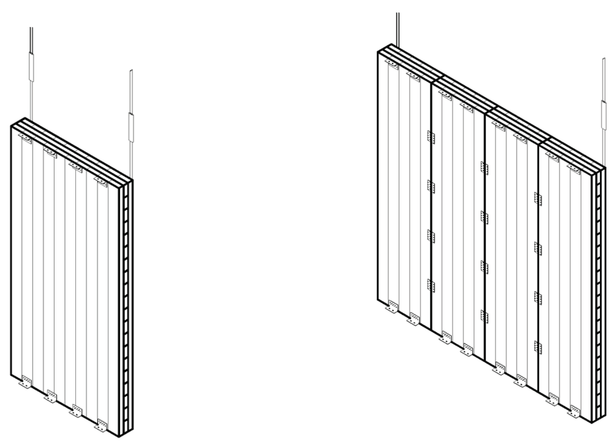


Figure 4: *Illustration of Rocking Behavior of Seven Individual Panels in a Multi-panel CLT Shear Wall*



(a)

(b)

Figure 5: *Typical CLT shear wall for a) single-panel configuration and b) multi-panel configuration*

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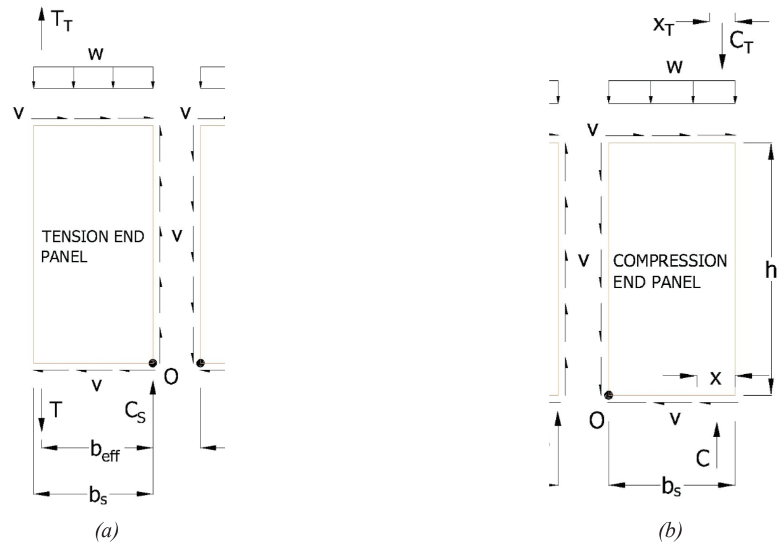

Figure 6: *Free-body Diagram for (a) the Tension End Panel and (b) the Compression End Panel of the CLT Multi-panel Shear Wall*

Additional Resources for Seismic Requirements

Background information on the development of the CLT shear wall system is available in General Technical Report FPL-GTR-281 *Determination of Seismic Performance Factors for Cross-Laminated Timber Shear Walls Based on the FEMA P695 Methodology* [15]. The report includes testing, modeling, and archetypes that led to the development of seismic design coefficients for the CLT shear wall system.

The NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, Volume I: Part 1 Provisions and Part 2 Commentary, 2020 Edition, FEMA P-2082-1 [16] includes design requirements for CLT shear walls. As a predecessor to requirements in ASCE 7-22 and SDPWS, the NEHRP requirements are similar but not identical to those appearing in SDPWS. The 2020 NEHRP *Recommended Seismic Provisions: Design Examples, Training Materials, and Design Flow Charts*, FEMA P-2192 [17], contain design examples based on the 2020 NEHRP Provisions. FEMA P-2192 includes an approximate 25-page example of the CLT shear wall system following the requirements of ASCE 7-22 and SDPWS. The example features the seismic design of cross-laminated timber shear walls used in a three-story, six-unit townhouse cross-laminated timber building of platform construction.

5 2021 IBC FINAL PRODUCT – CODE CHANGE SUMMARY (Type IV-A, IV-B, IV-C)

5.1 2021 IBC

The efforts led by the TWBAH Committee resulted in the inclusion of tall mass timber provisions in the 2021 IBC [3]. Three new building types were added to the IBC, called Type IV-A, IV-B, and IV-C construction, permitting the tallest ever code accepted wood construction in the US. A brief summary of the maximum story limits and building heights allowed in the 2021 IBC is presented in Table 3.

Table 3: *New 2021 IBC Building Types and Height Limits*

Building Type	IV-A	IV-B	IV-C
Maximum # Stories[1]	18	12	9
Maximum Building Height	82m/ 270ft	55m/ 180ft	26m/ 85ft

[1] Based on Occupancy Use of the building

These building code provisions have already been adopted by several state and local jurisdictions, and will continue to be adopted by municipalities across the US.

5.2 2018 NDS

A product chapter for CLT was introduced in the 2015 NDS and updated in the 2018 NDS [18]. Reference to the 2018 NDS was updated in the 2018 IBC and is retained in the 2021 IBC. The NDS specifies that the design procedures for CLT are only applicable to materials manufactured in accordance with production standard ANSI/APA PRG-320 [5] and includes provisions on structural design, connection design, and fire design. The NDS allows designers to choose one of two design methods, Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD) for CLT structural and connection designs. However, it limits fire design provisions to ASD designs only.

5.3 2021 SDPWS

The 2021 SDPWS [2] is the first edition of the standard to include provisions for CLT-based lateral-force resisting systems (LFRS). Coupled with the previously discussed seismic factors published in ASCE 7-22 [11], designers can use CLT diaphragms and shear walls to resist loads due to wind and seismic forces. SDPWS allows for designs using both ASD and LRFD.

6 FUTURE PLANS

6.1 2024 IBC Approved Code Change

The TWBAH Committee established early on during the 2021 IBC development process that only criteria based upon actual tests would be utilized to evaluate the fire performance of CLT. Over 600 data collection points were utilized during the ATF Fire Tests. This extensive data collection was done in part, to facilitate additional follow-up testing. The conservative, relatively small, unprotected portions of both walls and ceilings were justified under the testing criteria performed at the ATF laboratory because the CLT utilized for all five tests was not fabricated with fire-resistant adhesives per the ANSI/APA PRG320-18 standard [5]. In fact, the standard had not even been drafted in 2017 during the time of the ATF tests. The fire-resistant adhesive requirements of ANSI/APA PRG320-18 prevent failure at the glue line of the CLT within the test compartment. Pursuant to the previous fire tests at ATF, recorded compartment temperatures decayed below the point at which reignition of exposed CLT would occur (572°F/300°C). A successful test meant that the compartment temperature dropped below 300°C prior to the conclusion of testing at 240 minutes.

Based on recent RISE tests, a code change proposal, submitted and approved under the ICC governmental consensus process for the development of the 2024 IBC, will permit mass timber ceilings to be exposed for ceiling areas not to exceed 100% of the floor area in Type IV-B Construction. For design professionals to take advantage of this provision, the walls must retain the non-combustible sheathing requirements (typically a minimum of two layers of 5/8 in. or 16mm Type X gypsum board) for the Type IV-B Construction. Additionally, all other stringent active and passive fire protection requirements would apply for these structures which are permitted to be up to twelve (12) stories and one-hundred and eighty feet (180 ft/55 m). This code change permits design professionals to showcase the aesthetically pleasing properties of wood, without sacrificing any reduction in fire performance.

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