Fire Safety Engineering of Tall Timber Buildings in the USA

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ABSTRACT: Model building codes in the United States limit timber construction to six stories, due to concerns over fire safety and structural performance. With new timber technologies, tall timber buildings are now being planned for construction. The process for building approval for a building constructed above the code height limits with a timber load-bearing structure, is by an alternative engineering means. Engineering solutions are required to be developed to document and prove equivalent performance to a code compliant structure, where approval is based on substantive consultation and documentation.

Architects in the US are also pushing the boundaries for the fire engineering design, requesting load-bearing timber be exposed and not fully encapsulated in fire rated plasterboard. This provides an opportunity for the application of recent fire research on exposed timber to be applied, and existing methods of analysing the impact of fire on engineered timber structures to be developed further. This paper provides an overview of the performance based fire safety engineering required for building approval and also describes the engineering methodologies that can be utilised to address specific exposed load-bearing timber issues; concealed steel plate connections for glulam beams; and the methodology to address areas of exposed timber.

KEYWORDS: Tall timber buildings, fire safety, connections, exposed timber, performance based design

1 INTRODUCTION

Multi-storey timber buildings are being planned and constructed globally. The demand for these types of buildings is due to the availability of innovative materials like cross-laminated timber (CLT), but also based on the need for green and sustainable architecture. The recent United States Department of Agriculture’s (USDA) Tall Wood Building Competition¹ has awarded two winners that will soon start construction in the US; a ten storey residential building in New York (475 West 18th Street²) and a twelve floor mixed office and residential building in Portland (Framework³). Both the Portland and New York buildings will be using a combination of glulam as the primary structural gravity frame, with CLT floors. Both buildings will also include CLT for walls. These new buildings introduce a significant step-change in the design and construction of tall timber buildings in the US. The USDA competition has encouraged other developers and architects to plan tall timber buildings and more are expected within the US in the near future.

With the resurgence of timber as a construction material in the US, there is significant interest in the fire safety methods being utilised. This paper provides an overview of the methodology and process for fire safety alternative engineering solutions, to prove compliance to the International Code Councils International Building Code⁴ (IBC). The paper also describes an engineering methodology to address specific timber framed building issues, including concealed glulam connections, where the timber is exposed within a compartment; and provides a methodology for the analysis of areas of exposed timber within a residential unit.

1.1 CONTEXT AND BACKGROUND

While combustible, the inherent fire resistance of mass timber building elements, such as CLT and glulam is distinctly different from the minimal fire resistance of light timber frame members. Sawn and engineered timber have fire properties that have been very well researched and understood, with significant fire testing undertaken in North America⁵. Timber buildings that utilize engineered timber products can be designed with fire resistance ratings (FRR) of 120 minutes or more, without relying on additional passive protection and hence can be used as the primary structure in taller buildings, where fire ratings are normally more than 60 minutes.

2 MODEL CODE COMPLIANCE

Each State and some cities within the US adopt one or more model building codes. All 50 states adopt the IBC⁴, with some states also adopting NFPA 101 ‘Life Safety Code’⁶. Each State adapts and amends the model codes to provide the basis for construction compliance.
Timber construction is referred to as combustible construction in the IBC. Concrete and steel construction is referred to as non-combustible construction. Recently the 2015 IBC has been updated to recognize CLT for use as a building material. The IBC requires buildings above 75ft (defined as “high-rise”) to have an increased level of fire protection and structural performance. Hence timber is limited to low and medium rise buildings only. Building approval for tall timber buildings is a significant barrier in the US, given the code limitations coupled with the unfamiliarity of mass timber as part of the primary structural frame.

2.1 HIGH-RISE TIMBER BUILDING – PATH TO PERMIT

High-rise construction is represented by non-combustible construction Types IA and IB, whereby the load-bearing structure (i.e., columns, beams, floors and any load-bearing walls) are required to have a sufficient FRR for these elements to survive full burn out of a fire, where the sprinklers have failed and the fire department has limited intervention. The building is to remain structurally sound even in this highly unlikely scenario. The required FRR are increased to 120 to 180 minutes for high-rise buildings. There is a significant difference in expected structural performance for a high-rise building, when compared to a medium-rise building. The approach of addressing fire ratings for the full fire burn out a high-rise building is consistent in codes internationally.

As Type I requires non-combustible construction, approval for a high-rise timber structure requires the proposal of an alternative engineering design. This is permitted by the “Alternative materials, design and methods of construction and equipment” clause. Undertaking an alternative engineering approach (or a performance based design) is subject to approval by the authority having jurisdiction (AHJ). The methodology for developing an alternative engineering design varies among states in the US and can also vary within the state, where an AHJ may not permit an alternative engineering approach to be developed. The process of approval is typically based on proving that the tall timber building will provide a level of fire safety that is equivalent in performance to a code compliant building of the same height, area and use. A tall timber building is a very new form of construction and hence will undergo intense approval scrutiny as it progresses through to the approvals stage.

The engineer is required to follow a detailed process of documentation and communication with the AHJ. The initial step is to meet with the AHJ to discuss the proposed building design and form of construction, to gain approval to move forward with an alternative engineering design. As the architectural plans move into Schematic Design, a Concept Fire Safety report is documented to confirm the basic building parameters. This report is used for discussion with the AHJ and fire department, to gain an in-principle agreement on the approach. The report would typically include a detailed code review to identify key areas of code non-compliance and the methods for providing solutions to gain a permit. From the author’s experience, meetings at this stage of the project will cover a wide range of topics related to fire safety in timber. Topics of discussion, followed up with detailed documentation include timber fire ratings, evidential fire testing, FRR of connections, impact of exposed wood on fire size, adhesive fire safety, timber combustibility, fire safety during construction and methods for showing equivalence. Meetings also provide the opportunity to discuss relevant timber research, analysis methods and data availability. As part of the process, comments, meeting minutes and documentation queries are all recorded as part of the engineering process.

Once an in-principle agreement on the Concept Fire Safety report has been agreed, then a detailed Fire Strategy report can be documented to support the building design. This report is based on the Developed Design documentation for the project and includes detailed background on fire testing for timber components, includes all calculations, analysis and drawings, to prove that using timber as part of the primary structure provides an equivalent level of safety to a non-combustible structure. Supporting information from relevant suppliers and gaps in data can also be identified. Where fire testing is required, this will be carried out to fill in the current knowledge gaps and to assist with the approvals. Again, this report and its findings are discussed in detail with the AHJ and fire department for approval, which may take a number of meetings. Once the report is agreed in-principle, then all requirements are included within the building permit documentation. The process from initial meeting to approval is a time-intensive process and requires support from the project team.

3 FIRE TESTING – INSUFFICIENT DATA FOR ENGINEERED TIMBER

Within the US, as with most countries, all load bearing structural elements, interior and external finishes are required to be fire tested to ascertain if they meet criteria set by the IBC.

An issue for tall timber buildings in the US is the lack of available fire testing of engineered timber products, where those tests are carried out in the US to meet the IBC. This is of particular concern for CLT supply, where no U.S.-based fire tests have been carried out on a CLT floor, with the underside exposed. There are also few fire tests for CLT connections, especially for fire ratings of 120 minutes (required by the IBC for high-rise buildings), and few fire tested penetration seals, for cables, pipes and ducts. The lack of fire testing for engineered timber products has resulted in slower building approvals, as all components need to have the required proof of FRR when the design is submitted for permit.

For projects that require a 60 minute or 120 minute FRR from CLT floors or walls, there are fire tests that can be used to assist with permit approval, with the most relevant carried out in Canada, and documented within the CLT Handbook. The CLT Handbook is becoming more
widely accepted as a design guide and the analysis correlations for an FRR can assist and inform an AHJ of the expected CLT thickness for a required FRR.

Where an architect requests that glulam beams or columns are exposed, another limiting factor is the lack of fire tested or constructed 60 minute and 120 minute FRR glulam beam-to-column, or column-to-column connections available. This is not a US based issue, with a significant lack of fire test data available to all fire safety engineers on methods for achieving an FRR for a concealed steel plate connection. This issue is covered in more detail below.

An issue that has also arisen within the US and requires further detailed analysis and fire testing is where an exposed glulam beam supports an area of exposed CLT floor. It is not evident that this arrangement has been fire tested as one assembly before. The issue to be addressed is the increased char rate of the glulam beam, given the adjacent location of the exposed CLT that the beam supports. It is expected that there would be an increased charring rate in the glulam beam, due to the adjacent exposure of the burning CLT. The CLT heat flux, combined with the fire induced heat flux, may result in a higher char rate in the beam. There appear to be no correlations that address the increased charring rate in the glulam, due to the adjacent exposure of the burning CLT. Initial calculations by the author to address the issue of a relatively higher incident heat flux at the beam have been based on a 20% increase in beam char. The increase in char rate due to the incident flux from the CLT has been based on measured heat flux from CLT fire tests\(^\text{1}\) and the methodology described by Butler\(^\text{10}\).

To assist with building approval and to provide current and future high-rise buildings with useable timber solutions, which is a primary aim of the Tall Wood Building Competition, a number of fire tests are being funded by the USDA\(^\text{1}\). These fire tests will meet the IBC and ASTM E119\(^\text{1}\) and include CLT walls and floors, CLT floor assemblies and a number of connections. These tests will provide new information to the timber construction industry, once completed.

4 CONNECTIONS IN GLULAM BEAMS AND COLUMNS

4.1 INTRODUCTION

Connections must be designed to have strength and a fire resistance rating equal to that of the connecting members. Connections in engineered timber, such as glulam, are an unresolved design issue, as there is no clear methodology to assess their capacity under fire, when the timber is exposed and not clad behind fire protective plasterboard. Connections in timber are the weakest parts of the building structure.

Connections with concealed steel connectors, which is the preferred architectural method, are difficult to engineer as strong elements resisting fire. Steel is a very good conductor of heat and transfers heat to the connected timber members, leading to increased charring and a faster reduction in the strength of the timber close to the connection, resulting in an earlier than expected failure time\(^\text{11, 12, 13, 14}\). Following an in-depth literature review on timber connections exposed to fire, the following has been found:

- There are many historic examples of connections in design guides, but little evidence of proven FRR. The industry is currently using prescribed connections that may (or may not) provide a stated FRR, given currently available evidence based fire testing.
- Achieving an FRR of 60 minutes or more requires significant depth of timber cover and there are only a few correlations to calculate the FRR, with limited applicability. There are few fire tests on concealed steel connections for an FRR of 60 minutes.
- The load carrying capacity of a concealed steel connector is impacted by the heat transfer into the timber by exposed or partly concealed dowels or bolts.
- The key design inputs considered to be critical to connection design and not well defined are the rate of char at the connection and the depth of the heat affected layer.

4.2 APPLICATION OF CURRENT METHODS

A preferred glulam connection for architects is a concealed timber-steel-timber connection, with a central steel plate, potentially with dowels, located behind solid timber plugs. This is also relatively easy for a structural engineer to design. For a tall timber project in the US, this type of connection will require an FRR of 120 minutes.

The methods available to a fire safety engineer to analyse the FRR for a glulam connection are from American Wood Council’s Technical Report No. 10 (TR-10)\(^\text{15}\) and EN 1995-1-2 Eurocode 5 (EC5)\(^\text{16}\). Both TR-10 and EC5 have an approach of limited validity up to 60 minutes, using the reduced cross-section approach. Both methods are based on determining a char layer for the timber that surrounds the connection and provides the “cover” to protect the connection from the heat of the fire.

The TR-10 approach is based on the nominal char rate being increased by 20% to account for corner rounding, fissures and a reduction in strength and stiffness for the zero strength layer. The zero strength layer is located directly behind the char. TR-10 requires that the timber cover to protect the concealed connection is determined through calculating “\(\text{a}_{\text{char}} \cdot 1.2\)”, where the value of \(\text{a}_{\text{char}}\) for a 60 min FRR connection is 0.76mm/min (1.8in/hr). Hence the timber cover required is calculated as 38.1mm. The distance from the bottom of the member to the connection is also required to be at least 38.1mm.

The “Reduced cross-section method” within EC5 is based on the notional char rate, which includes corner rounding and fissures, and determined as \(\text{f}_{\text{CH}} \approx 0.7\text{mm/min}\) for glulam. To account for the loss of strength and stiffness
behind the char (zero strength layer), an additional 7mm is added to the total width of char. For a dowelled connection behind timber plugs to achieve a 60 min FRR, the cover depth is required to be 49mm.

The two approaches produce different results, with TR-10 providing cover to dowels of 38.1mm and EC5 producing cover to timber plugs of 49mm. The difference between the values was cause for concern and based on the literature review completed, it was determined that to provide a glulam beam to column connection that is able to achieve a 120 min FRR, a new methodology for fire protection was required to be developed.

4.3 ALTERNATIVE APPROACH
An alternative approach to fire design of connections has been under development for a number of years by the author. The methodology will be verified through future fire testing.

4.3.1 Impact of Temperature on Timber Strength Properties
The approaches from TR-10 and EC 5 are based on a number of assumptions. Firstly, the assumed char rate for the timber can be used to determine a thickness of timber that has no strength and provides insulation. The next assumption is that the timber directly behind the char has zero strength, for a set depth (zero strength layer). The third assumption is that the timber directly behind the zero strength layer has the strength and stiffness of cool timber. In the author’s opinion, these assumptions need to be challenged as they may be non-conservative.

To assess the ability of a timber member to resist applied loads at a typical beam-column shear connection, there are two key design inputs (below), which are discussed further in the next sections:

1. Rate of char for the timber that surrounds the connection and provides the “cover”, to calculate the char layer.
2. The depth of the “heat affected layer” located directly behind the char, which includes the zero strength layer, where the timber strength and stiffness are impacted by the fire.

4.3.2 Char Rate
It is evident from fire testing carried out that the char rate at connections is higher than at other parts of a beam or column\textsuperscript{13, 14, 17}. The char is influenced by:

- If any part of the connection is exposed, the char rate is increased due to the connections transferring heat into the timber.
- For concealed connections, the steel plates and dowels/bolts attract heat into the connection, resulting in an increased char rate.
- The choice of dowels or bolts influences the char rate, with bolts having a greater impact due to the area of the bolt head, washers and nuts.
- Glulam beams and columns that are exposed timber may have an increased char rate if there is an exposed timber floor adjacent. This increased char rate needs to be accounted for at the concealed connection.
- Real fires typically have higher temperatures for the initial period of fire growth, when compared with standard fires. Hence the heat flux received will induce higher initial charring rates.

To account for the increased char rate at the connection, a char rate of 0.8mm/min is recommended for analysis of concealed connections, based on the available fire test research. Further research is needed to confirm an accurate value for concealed plate connections, for a 60 or 120 minute FRR and for exposure to real fires.

4.3.3 Accounting for Reduced Strength and Stiffness
It is evident from fire testing on full size connections that they may fail earlier than expected, in particular when they are designed to achieve 60 minutes FRR\textsuperscript{11, 18, 19}. It is also apparent from fire testing that the failure mode typically reached is a large deformation resulting from an embedment failure. This may lead to a full shear failure or splitting of the timber\textsuperscript{17, 20, 21}. The embedment failure is typically evident from increased ovalisation that occurs around the dowels or bolts, due to the weakening timber strength and stiffness. As the timber starts to heat up, the ability to resist shear induced by the bolt or dowel connector reduces and embedding failure occurs. Designing for the reduced embedment strength is a key factor in achieving a predictable FRR in a connection.

The layer of timber directly behind the char is reduced in strength and stiffness, as fire testing has shown. Accounting for the loss of strength in the timber directly behind the char and the specific depth of that weakened timber then becomes critical for a concealed steel connection, where embedment failure is to be prevented. Determining the depth, strength and stiffness of the heat affected layer and then designing a connection to be located within the close to full strength timber will provide the basis for a connection to withstand a longer duration fire exposure. The approach of increasing the char rate by 20% (TR-10) or adding 7mm (Eurocode 5) may be effective for an FRR of 30mins, but appear to be non-conservative for longer duration fires.

Research on the impact of temperature on embedding strength is key to predicting an FRR for longer duration fires\textsuperscript{17, 22, 23}. The change in embedding strength has been measured extensively and correlations do vary. For timber heated to 100°C, the embedding strength is accepted as being reduced by approximately 55% in comparison to the 20°C value (see Figure 1). Strength loss continues with increasing higher temperatures.
Hence, for a connection to retain sufficient capacity for the duration of a fire, the connection must have timber cover to retain adequate embedment strength. From the author’s analysis, a connection should be designed such that the timber at the connection retains 80% of its ambient value embedment strength. Based on the above relationship (Figure 1), a temperature of 60°C or below is required to retain 80% or more of the embedment strength.

The properties of the heat affected layer have been determined in various research papers, indicating the zero strength layer is dependent on the width of the member and the time of fire exposure. The work by Frangi and Fontana has provided a detailed description of the “thermal penetration depth”, the depth behind the char where the timber is at ambient conditions, even when subject to a long duration fire. Thermal penetration depth is estimated as being 25mm to 50mm, and at 60 minutes of standard fire exposure, specifically, 30mm deep. To account for this heat affected layer, the temperature of the timber is required to be calculated, based on distance from the back of the char layer. This can be calculated from existing fire test results, as shown in Figure 2 and Figure 3, or through calculation.

Based on the empirical results reviewed for the thermal penetration depth, a depth of 20mm to 40mm will maintain a timber temperature of 60°C, which is consistent with the method from Frangi and Fontana. A value of 30mm is used for 60 minute FRR and 40mm is used for 120 minute FRR. The values chosen are slightly conservative as there will also be a difference in actual thermal penetration depth, when that member is exposed to a real fire. The values used from literature are based on standard fire exposure.

4.3.4 Protection Required for Connections

Based the above approach, a depth of timber cover required to protect a connection, i.e., to allow for protection of the dowels, bolts or steel plates, can be calculated such that the timber retains 80% of its embedment strength. The wood cover required for a 60 minute FRR is 78mm – based on a depth of char of 48mm (0.8mm/min x 60mins) plus a depth of heat affected layer of 30mm. For a 120 minute FRR, the timber cover to the connection (plugs or cover to the plate bearing connection) would be 136mm.

Current research on concealed timber connections has shown that fire testing may result in a failure time earlier than expected. Hence, a different approach for the fire design of timber connections has been developed based on the key fundamentals of char rate and heat affected layer. Finite element modelling has shown the approach to be effective and fire testing of full size connections will provide more conclusive results, to be completed in 2016.

5 EXPOSED TIMBER – DISCUSSION OF ISSUES AND METHODOLOGY FOR SOLUTION

Architects in the US are requesting more timber is exposed within their buildings. A common theme is exposed timber at the ceiling (underside of the CLT floors). The contribution of exposed timber to compartment fires is an important issue that has limited the development of timber buildings in some countries, particularly in a residential setting, where the timber may
be desired by architects to be exposed on the ceiling and/or walls.

5.1 EXPOSED TIMBER – ISSUES TO BE ADDRESSED

A building design may be based on areas of exposed load-bearing timber, that may include columns, beams or the underside of the timber floor, or all parts of the structure. For low-rise and some medium-rise buildings, codes typically permit greatly reduced fire safety requirements and allow buildings with a zero FRR. Hence, timber can be exposed and code compliant. Interior finishes may also be relaxed. For a high-rise building, the expectation for the FRR of the load bearing elements is that they would survive full burn out of a fire, where the sprinklers have failed and the fire department has limited intervention.

Accounting for areas of exposed timber (not clad in fire rated plasterboard) is a significant technical challenge to analyse and introduces challenges for fire safety. There are three aspects to be addressed for exposed timber.

The first aspect is having combustible interior finishes as part of a building. Building codes permit combustible interior finishes within high-rise buildings, including timber. Timber as an interior finish will introduce fire load, such as when timber panelling is used on floors or walls and can influence fire growth early in the fire development. A coating may be required to limit flammability, but exposed timber within a compartment is not a new problem. However, flammability for the exposed timber still requires to be proven and the IBC requires fire testing to ASTM E84. The IBC allows timber to form part of the combustible fuel as an interior finish within an office or residential building and does not place limits on its location or thickness, provided it meets with Class C, when tested to ASTM E84, when sprinkler protection is provided.

The second aspect to be addressed is exposed load-bearing and non-load-bearing timber within a compartment, such as panelling, floating floors, load-bearing beams, columns or the underside of a CLT floor, and how that exposed timber impacts on the compartment fire. The fully developed fire peak heat release rate (HRR) and fire duration will be increased due to the added combustible fuel available from the exposed timber, when compared to a compartment without any exposed timber. How the fire decays is influenced by the timber, once all the fixtures and furnishings have been consumed, is also of concern. The issue to be addressed is that the energy released from the fire, influenced by the exposed timber, may result in the FRR provided for structural stability and compartmentation being insufficient.

The third aspect to be addressed is where a building has exposed timber as part of the load-bearing structure. Where a fire can become fully developed (in the unlikely situation of a sprinkler system failure), then the load-bearing structure will form part of the combustible fuel, contributing to the fire development. The IBC requires load-bearing structure to be non-combustible. The FRR for the structure is required to be designed appropriately to resist the expected fire load, including that fire load of the exposed load-bearing timber.

5.2 FIRE TESTING FOR EXPOSED TIMBER

Fire testing has shown that having large areas of exposed timber will impact on the fire size and the fire duration, as the exposed timber provides an additional volume of combustible fuel. This occurs whether the timber is an interior finish or part of the structure. Fire testing has been carried out on exposed CLT panels (walls or underside of floor) in Canada and Europe and more testing is planned in Europe, UK, Australia and the US over the next 12 months. The aim of the fire testing has been to determine a method for predicting the increase in fire size and duration, based on the area of exposed CLT within a compartment.

The fire testing of exposed CLT has shown that where there are adjacent exposed timber surfaces (such as a wall and underside of a floor; or two walls), once ignited, the two surfaces will re-radiate between the surfaces, resulting in a longer duration fire (when compared to a compartment with non-combustible finishes). This longer duration fire, which continues even after all the fixtures and furnishings in the space have been burnt, can lead to failure in the load-bearing elements as the exposed timber elements continue to burn and the fire decay occurs at a much slower rate.

More specifically, Medina’s fire testing showed that where two CLT walls were exposed, being 53% to 59% of the total internal wall surface area (Tests 1 and 2 of Figure 4), the HRR and fire duration were influenced, as re-radiation occurred between the exposed timber surfaces. Medina also showed that where one wall of CLT is exposed, being 29% of the total internal wall surface area, the compartment fire is not significantly impacted (Test 3, Figure 4).

Figure 4 – Results from Medina and McGregor’s research, showing the difference in fire size (HRR) for a CLT room with full gypsum protection, one wall CLT wall exposed (test 3), two walls exposed (tests 1 and 2) and all walls exposed (fully unprotected).
McGregor’s testing showed that where all the internal timber surfaces were exposed, there was a significant influence on HRR and fire duration, with HRR increasing by 60% over that of an identical non-combustible compartment. These tests are an important cornerstone for addressing exposed timber within a compartment.

If the CLT is susceptible to premature failure of the plys at the adhesive interface, before complete charring (referred to as delamination, or stickability), then the longer duration fire can result in more CLT being consumed by the fire, with the potential for spikes in HRR when the ply interface is reached by the char front. The spike in HRR is due to the increased fuel that becomes available due to the unburnt delaminated timber and the unburnt timber that is exposed. If too much timber is exposed, then the total fuel within the space (furniture, fixtures and exposed timber) can result in a fire that extends longer than the installed fire resistance ratings.

It should also be noted that fire tests involving two exposed CLT surfaces appear to become tests with multiple surfaces exposed, as the test continue and the fire rated plasterboard fails. Hence, data based on two exposed CLT surfaces have to be considered carefully as the test results often conclude with most CLT surfaces exposed and burning.

5.3 METHODOLOGY FOR ASSESSING LIMITED AREAS OF EXPOSED TIMBER

The permitted square area of timber that is exposed requires an assessment method and currently, there are no methods available for addressing exposed timber. There is an area of exposed timber that is always going to be acceptable within a compartment, but there is also a limit to how much timber can be exposed before the timber significantly changes the HRR and duration of the fire. Determining that limit is key to the design for permitting a safe amount of timber to be exposed within a compartment. The following sections provide an introduction and overview to the methodology that the author first applied to a building in 1997, for use with exposed tongue and groove floors and exposed timber structure. The approach has continued to be used and refined over a number of years and applied to a number of different projects and can also be applied to CLT, with some limitations.

For exposed CLT, based on the fire test information that is available, the following limitations have been applied:

1. Only one timber surface can be exposed in any compartment, being either the underside of a CLT floor or a CLT wall, so that two exposed surfaces are not adjacent to each other, to prevent re-radiation between surfaces;
2. Where the load-bearing timber is not exposed, it is required to be protected by fire rated plasterboard that prevents the timber being exposed for the duration of the expected fire;
3. The exposed timber needs to be limited in area such that it does not impact on the required FRR for the compartment (separating walls or floors or load-bearing structure).

5.4 CALCULATION METHODOLOGY

Two methodologies are used for assessing limited areas of exposed timber. The first approach is based on “hand-type” calculations, via a spreadsheet and this is detailed below. This has a number of conservative assumptions to provide a methodology that allows for relatively quick analysis, and in turn, the limitations of the methodology should be acknowledged. The second approach, which is not covered within this paper, is based on using a detailed computational fluid dynamics (CFD) modelling program to provide more accurate analysis; however, this approach does require significant user input and computation time.

5.4.1 Compartment Fire and Timber Char Rate

The char rate for timber when exposed to a fire is directly proportional to the heat flux received and once timber is exposed to a heat flux above 12kW/m², which is the limit for piloted ignition, timber starts to char.

To accurately account for the charring within the exposed timber, such as CLT, a time-temperature curve for the compartment is first required, such that a heat flux can be determined at the timber location. This approach for determining char rates differs from that recommended in guidance such as EC 5 or TR-10, but is considered to be more accurate. The approach of using a char rate value based on an expected real fire accounts for the higher temperatures that occur in the initial stages of the fire development, when compared to a standard fire. The decay period can also be accounted for.

5.4.2 Hand Calculation Method

The hand calculation methodology is based on the expected total fire load of furnishings and fixtures, and the additional mass of fuel due to the combustion of the exposed timber that has been consumed during the fire. The compartment fire, including exposed timber, should release less energy than that of the standard time-temperature curve, for a 60 minute or 120 minute FRR.

The exposed timber is addressed though a “lumped mass” model, whereby the additional timber that will be consumed by the fire is “lumped” together as one fuel load item and assumed to be consumed by the fire over the duration. The exposed timber will start to influence the fire when there is sufficient source of heat applied, such that charring occurs (heat flux is more than 12kW/m²). Hence, at the beginning of the fire and once the fire has decayed, the exposed timber will not contribute to the overall compartment fire as it will not char. It is assumed that once the heat flux is below 5kW/m², the exposed timber will stop charring and contributing to the fire.

The methodology to account for the exposed timber is therefore:

1. Calculate the area of exposed timber within a compartment (assuming an area of exposed CLT).
2. Develop a time-temperature curve for the compartment (fire growth and decay), assuming for the initial calculation that all surfaces have non-combustible finishes only (fire rated plasterboard assumed), to determine pre and post flashover conditions. Assume a typical compartment fire load energy density (FLED) of a typical residential unit (300 to 400MJ/m²) or an office floor (500 to 600MJ/m²).

3. Consider the decay period of the fire to be independent of the type of fuel burning (moveable fuel or timber) for this initial calculation (non-conservative assumption at this stage).

4. From the time-temperature curve developed, calculate the heat flux at each time step where the exposed timber surface is located (such as an exposed ceiling).

5. Assume that the exposed timber surface receives the same instantaneous heat flux across the whole surface, as a conservative assumption, i.e. for a ceiling, assume a uniform gas temperature in the hot layer (conservative approach). For a wall, assume a weighted average instantaneous heat flux across the wall, due to the differences in temperature at the top and base of the wall. For simplicity, a uniform instantaneous heat flux based on the temperature at two-thirds of the height above floor can be used and applied across the whole wall, as a conservative approach.

6. Calculate the charring rate, which is based on the heat flux at the exposed timber surface\(^{10}\), for each time step.

7. Based on the fire duration, calculate the depth of char of the exposed timber based on the varying heat flux. Charring is accounted for when the heat flux at the exposed timber surface is 12kW/m² or more. When the heat flux is less than 5kW/m² (average), charring is considered to stop and the exposed timber is expected to self-extinguish.

8. Compare the average char rate for the duration of the fire with the calculated char rate for CLT\(^{9}\). Use the greater of the calculated char rates. Do the same for glulam members, referring to TR-10 or EC5.

9. From the depth of char, calculate the mass of timber that would be consumed by the compartment fire, based on the total fire duration and the char rate. This is based on the area of exposed timber (m²) multiplied by the depth of char which equals a volume of burnt timber. The timber density then provides a mass of burnt timber.

10. The mass of burnt timber is converted to energy released (typical timber value of 18MJ/kg) to produce MJ and dividing by the area of the compartment, a FLED for the burnt timber (MJ/m²) is determined.

11. Re-calculate the compartment time-temperature curve (starting at item (2) above), with the new compartment fuel load including the mass of burnt timber, i.e. initial FLED of fixtures and fittings (MJ/m² from item 2) plus the contribution of burnt timber (MJ/m² from item 10). The assumption for the interior finishes can also be altered for this step, as the compartment time-temperature curve will be based on the weighted average of exposed timber and plasterboard (impacts on assumption of heat loss through surfaces).

12. The additional fuel load due to burnt timber will increase the fire HRR. Accordingly, a new time temperature curve will be calculated with a longer duration.

13. The new time-temperature curve is then used to calculate the heat flux at the exposed timber and the time of exposure, as per steps (4) to (8) above. A new mass of burnt timber is calculated and a new additional FLED based on the exposed timber is calculated, as per steps (9) to (10).

14. Repeat the process, steps (2) to (11) until the additional FLED due to the exposed timber starts to converge. The process is typically repeated 4 to 7 times until the increase in FLED is less than 5% between steps.

15. Once the additional compartment FLED has stabilized to less than 5% difference between iterations, the final time-temperature curve for the compartment, including the exposed timber that will be consumed has been determined.

16. Where there is no convergence, the area of exposed timber has to be reduced, such that convergence can occur.

17. A sensitivity assessment is carried out, varying window area available for ventilation and the initial FLED, to gain a range of values.

18. The time-equivalence (FRR compared to a standard time-temperature curve) for the compartment is calculated using the Pettersson\(^{17}\) method or the method from Eurocode 1, Part 1-2\(^{28}\), using the final FLED from above as the input fuel.

19. If the time-equivalence is more than the required 60 minutes or 120 minutes, then the area of exposed timber is reduced and the results are re-calculated, starting from (2) above.

The time-temperature curves are evaluated based on a published methodology of compartment fire dynamics, such as those from Buchanan\(^{39}\), the SFPE Handbook of Fire Protection Engineering\(^{40}\) and Eurocode 1 Part 1-2\(^{28}\). The approach taken has been to develop time-temperature curves based on all options above and then compare the differences. The inputs that are required to be agreed with an AHJ include the initial FLED and the available compartment ventilation, which can be easily varied. All inputs require a sensitivity assessment.

The approach described above can be placed into a spreadsheet, with the results of the first iteration providing input into the second iteration and so-on. The variance in time temperature curve can also be plotted to show the difference in time-temperature curve for each iteration.

5.5 LIMITATIONS AND VALIDATION

The approach described above requires a number of assumptions and, in turn, contains a number of limitations. The assumptions are based on providing conservative outcomes. The method is considered to have a reasonable degree of accuracy for residential units,
given the fire research, testing and data available for these smaller area compartments (typically less than 200m²). The time-temperature curve development process is fairly well validated for residential units, with a variety of fuels. The approaches are considered to be less accurate for office floors, given the lower amount of fire test data available for full-scale office floor fires and the influence of travelling fires 41. Also of importance is the assumption regarding char rate, which can vary through the CLT section from 0.65mm/min to 1.1mm/min, even under a standard fire exposure 42. Using the varying heat flux method typically produces charring rates that are much higher than the typical design value for timber charring, of 0.65mm/min.

A check of the analysis methods has been carried out based on the available fire test data, primarily the results from Medina’s fire testing 43. As there is such a limited number of full-scale fire tests with CLT surfaces exposed, the validation exercise has been limited. The method has shown an accuracy in predicting fire duration that is within 20 to 30% of Medina’s results. A similar methodology developed using a CFD package is showing accuracies of within 15% with a single wall exposed. Further fire tests with a single timber surface exposed will assist with the validation and improvement of the methods.

5.6 APPLICATION

Using the above methods (hand-calculations and CFD analysis), three fire scenarios are then considered and include:

1) A scenario with non-combustible linings to all faces (IBC compliant);
2) A scenario with timber interior finishes to the walls, ceiling and floor (IBC compliant);
3) A scenario with exposed area of timber.

The analysis detailed above has shown that the additional fuel from the exposed timber of Scenarios 2 and 3 results in a compartment fire that has a higher HRR and a fire that is extended, compared with non-combustible linings (Scenario 1). The results from a range of residential units has shown that the amount of exposed timber has an impact on the fire duration. Calculations have shown that when one wall is exposed for 50% of the full length, or the underside or the floor is exposed up to 50% of its area, the increase in fire duration may still be within 60 minutes of the required FRR. Also, that the exposed timber available to influence the fire under Scenario 2 can be shown to extend a fire beyond the 60 minute FRR required.

The method for an office floor is based on achieving a 120 minute FRR and the results from assessing Scenario 3 have shown that where an area of the underside of the floor is exposed and is 30% or less exposed, the fire duration can still be kept within the required 120 minute FRR. The calculations for a floor are dependent on the overall floor area and ventilation available vary significantly with changing inputs. As with the residential unit, it has been found that the exposed timber available to influence the fire under Scenario 2 can be shown to extend a fire beyond the 120 minute FRR required.

6 CONCLUSIONS

The US is about to undergo a tall timber building evolution, with at least two new buildings of ten or more stories being designed at present and more to be constructed. There are a number of fire safety issues that need to be addressed as tall timber buildings become more prevalent and fire safety boundaries continue to be pushed. These buildings will come under intense approval scrutiny, as any new technology should. Details such as exposed areas of timber, proving fire ratings for connections, sealing of penetrations and fire risk during construction will all need to be addressed.

Of most importance though, is the building approval process to allow tall timber construction, which is highly reliant on a consultative approach to the fire safety engineering and an AHJ prepared to examine new technology. As more timber buildings using products such as CLT are constructed and the material becomes more familiar in the US, improvements in the understanding of fire safety for timber will occur, and potentially, so will changes within the IBC to allow for greater building height.

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REFERENCES

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