CROSS-LAMINATED TIMBER FAILURE MODES FOR FIRE CONDITIONS

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ABSTRACT
Tall timber building designs have utilized cross-laminated timber (CLT) significantly over the past decade due the sustainable nature of timber and the many advantages of using an engineered mass timber product. Several design methods have been established to account for the composite action between the orthogonally adhered timber plies. These methods assume perfect bonding of the adjacent plies by the adhesive. CLT designs methods for timber in fire have also been formulated. These methods rely on the relatively constant charring rate of timber to calculate a sacrificial layer to be added onto the cross-sectional area. While these methods focus on the timber failure mode of reduced cross section by charring, the failure mode of ply delamination is often overlooked and understudied. Due to the reduction of shear and normal strength in the adhesive, the perfect bond assumption can be questioned and a deeper look into the mechanics of CLT composite action and interfacial stress needs be conducted. This paper seeks to highlight the various design methods for CLT design and identify the failure mode of delamination not present in the current design codes.

KEYWORDS
Charring, Fire, Cross-Laminated Timber, Adhesive, Delamination, Failure Modes, Thermal Penetration Depth.

INTRODUCTION
The design and construction of tall timber buildings have increased in recent years. The Murray Grove Tower (29 m) in London and the Forté Building (32 meters) in Melbourne are currently the tallest two buildings in the world (Timmer 2011, Wells 2011, Wheeldon 2012). The Treet Building under construction in Bergen, Norway will be 49 m tall when completed (Abrahamsen and Malo 2014). Research into the feasibility of even taller designs has progressed as well. A report from mgb ARCHITECTURE + DESIGN demonstrated designs for 32 to 96 meter tall buildings (Green 2012). Skidmore, Ownings, & Merrill LLP (SOM) have produced the tallest design to date at approximately 120 meters (Skidmore Ownings & Merrill LLP 2013). In each of the designs, engineered mass timber products provide member sizes with the required structural strength and stiffness.

Engineered mass timber products rely on the composite action between two adjacent timber plies and the glue adhering them together for structural strength. Adhering multiple plies together offers many advantages over solid timber cross sections. The biggest benefit is the elimination of growth and other defects. The resulting cross section is structural stronger than solid timber and the resulting strength more reliable. Larger members capable of spanning longer distances are now possible where solid timber was incapable. The benefits of engineering mass timber are fully realized in cross-laminated timber.

Cross-laminated timber (CLT) is an engineered mass timber product where adjacent timber plies are glued orthogonal to one another. Cross laminating timber not only eliminates timber defects as in other glued timbers but also prevents dimensional expansion due to moisture. CLT has the capability of spanning in two directions (Gagnon, Bilek et al. 2013) allowing floors, slabs, and walls to be highly optimized and more economical.
SOM’s tall timber design even used CLT as part of the shear walls and cores to provide increase lateral stability against wind and earthquake loads (Skidmore Ownings & Merrill LLP 2013). As the market increases the use of CLT in structural frames, the number and accuracy of design methods developed as well.

METHODS OF CLT DESIGN

Currently, three different design methods are commonly used throughout the world. These and other methods are based on analytical and experimental solutions.

Mechanically Jointed Beams Theory

The Mechanically Jointed Beams Theory (Gamma Method) by Karl Möhler was originally developed for beams mechanically fastened by connections with a fixed stiffness $K$ spaced $s$ distance apart. The plies of the beam were oriented parallel with adjacent layers. The resulting beam had an effective stiffness of $EI_{eff}$ which was dependent on the efficiency of the connection, $\gamma$ (Eqs 1 and 2). Completely glued connections received a $\gamma$ of one and non-glued connections had a $\gamma$ equal to zero. This allowed the stiffness of the member to be dependent on the amount of slip in the connection (Gagnon and Popovski 2011). This methodology for glued beams can be found in Annex B of EN 1995-1-1:2004 (European Committee for Standardization 2004).

\[ EI_{eff} = \sum_{i=1}^{n} (E_i l_i + \gamma_i E_i A_i a_i^2) \]  

\[ \gamma_i = \left[ 1 + \frac{\pi^2 E_i A_i}{E_i l_i^2} \right]^{-1} \]

where:

- $i =$ layer number
- $E_i =$ Modulus of Elasticity
- $l_i =$ Moment of Inertia
- $A_i =$ Area
- $a_i =$ distance from centroid of each layer to the neutral axis of the cross section
- $l =$ span length

0 $\leq \gamma \leq 1$

Since CLT has orthogonally oriented timber plies, several corrections and assumptions had to be made to the Gamma Method. The first assumption was that layer oriented perpendicular to the direction of the span would carry no load. The perpendicular layers could be applied as fasteners to the longitudinal layers and the rolling shear stiffness, $G_R$, would act as the fastener stiffness between load carrying layers (Eq.3).

\[ \frac{s}{h_i} = \frac{\bar{h}_i}{G_R b} \]

where:

- $\bar{h}_i =$ thickness of ply
- $G_R =$ Rolling shear stiffness
- $b =$ width of panel

The maximum bending stress ($\sigma_{max}$), ply 1, can therefore found by equating both the local and global bending stresses in Eq. 4. Other stresses such as axial and shear can be found as well.

\[ \sigma_{max} = \frac{M E_i}{(EI)_{eff}} \left( \gamma_1 a_1 + 0.5 h_1 \right) \]
where:

\( M = \) applied moment

**Composite Theory**

The composite theory, otherwise known as the k-theory, as in the Gamma Theory uses an effective stiffness but in the form of composition factors which account for loading configurations and each individual layer’s properties. The main assumptions are linear stress strain relationship and Bernoulli’s hypothesis of plane sections. Each composition factor (Eq 5) is multiplied with each strength value and compared with the maximum stress applied. A list of composition factors can be found in (Blass and Fellmoser 2004, Gagnon and Popovski 2011). Shear deformations are not accounted for in this method.

\[
\sigma_{max} \leq f_{b,0}k
\]  

where:

\( f_{b,0} = \) bending strength  
\( k = \) composition factor

**Shear Analogy Method**

The shear analogy method accounts for shear deformations and is the most precise CLT design method according to Blass and Fellmoser(Blass and Fellmoser 2004). The bending and shear stress both incorporate the properties of each layer. The rolling shear stiffness is incorporated in the maximum deflection of a CLT slab by the introduction of the second term in Eq 6 (Gagnon and Popovski 2011).

\[
u_{max} = \frac{s}{3.84} \cdot \frac{qL^3}{(EI)_{eff}} \cdot \left(1 + \frac{48(EI)_{eff}k}{5(GA)_{eff}L^3}\right)
\]

where:

\( k = \) shear coefficient form factor  
\( q = \) distributed load  
\( L = \) span length  
\( (EI)_{eff} = \) effective bending stiffness  
\( (GA)_{eff} = \)effective shear stiffness

While each of the methods besides the k-method, assumes a degree of shear deformation, the shear is isolated in the plies themselves. All the methods assume complete bond adherence and no slip between the plies.

**METHODS OF CLT DESIGN FOR FIRE**

In the design of timber buildings, the structural components need to be designed against fire loads due to the combustible nature of timber. As timber increases in temperature, the wood slowly starts to decompose in a process known as pyrolysis. The wood breaks down into two major by-products: combustible gases and char. The char layer, which increases in thickness as the timber burns, builds to around a constant thickness of 25mm and insulates the rest of the cross section from the heat of the fire. Current methods of designing CLT for fire utilize the almost constant rate of charring to add a sacrificial layer of timber to the structural members.
EN 1995-1-2 defines the distance from the exposed surface of char to the char line, where pyrolysis occurs, as the charring depth. The char line is typically taken as the 300°C isotherm. The char depth is defined by Eq 7 for both one-dimensional charring and charring accounting for corner rounding (CEN 2004).

\[ d_{\text{char,0}} = \beta t \]  \hspace{1cm} (7)

where:

\( \beta = \beta_0 \) (one-dimensional charring rate) or \( \beta_n \) (notional charring rate accounting for corner rounding)

\( t = \) fire exposure time

To calculate the strength of a timber structural member, EN 1995-1-2 allows two calculation methods: the Reduced Properties Method (RPM) and the Reduced Cross-Section Method (RCSM). Both methods use the charring depth and assume the char contributes no strength to the structural capacity of the member. Both methods use a modification factor to account for the thermal penetration depth, the thickness of the member at temperature above ambient but below the pyrolysis temperature. Where the methods differ is that the RPM modifies the modulus of elasticity and the bending, tensile, and compressive strength of timber in the overall structural calculations. The RCSM specifies a “zero-strength” layer to be added to the char layer. This increased char layer is termed the effective char depth \( d_{\text{ef}} \) and accounts for the reduction in structural properties by eliminating a certain portion of the thermal penetration depth (Eq. 8). The remaining amount of the cross section is used to calculate the strength of the member assuming ambient temperature strength.

\[ d_{\text{ef}} = d_{\text{char,n}} + k_o d_0 \]  \hspace{1cm} (8)

where:

\( d_0 = 7 \text{mm} \)

\[ k_o = \begin{cases} \frac{t}{20}, & t < 20 \text{ min} \\ 1, & t \geq 20 \text{ min} \end{cases} \]

If the structural member protection, such as gypsum board, falls off the charring rate doubles until the char layer re-increases to 25 mm (Fig 1). The solid line in Figure 1 represents timber which chars at a constant rate. The dashed line represents a newly unprotected timber member which chars at double the rate until a charring depth of 25 mm is achieved. While EN1995-1-2 does not explicit mention CLT, char and ply delamination of CLT acts in a similar manner to protection fall off (Frangi, Fontana et al. 2006, Dagenals, White et al. 2013, Inghelbrecht 2014). The EN 1995-1-2 method of accounting for fire loads is purely a charring method and does not specify when char or ply fall-off occurs.
National Design Specification


\[ d_{ef} = \frac{\beta_n t}{z_{187}} \]  

(9)

where:
\( t \) = fire exposure
\( \beta_n \) = notional charring rate

NDS adds twenty percent to Equation 9 as its zero-strength layer. Unlike EN1995-1-2, the zero-strength layer is variable and depends on the actual char depth. While the maximum zero-strength layer for EN1995-1-2 is 7mm, the NDS zero strength layer increases beyond that (find out).

The NDS accounts for char and ply delamination by assuming the CLT layer falls off once the temperature of the adhesive reaches 300°C. Once the ply has fallen off, the char layer grows from zero thickness again. Aguanno (Aguanno 2013) recommended based on medium and full-scale tests to have ply fall-off be when the 300°C isotherm reached 12mm from the bond line.

SP Model

The last model to account for structural deterioration of timber and CLT due to fire is the SP Technical Research Institute of Sweden (SP) model (SP Technical Research Institute of Sweden 2010). The charring model recommended accounts for the char layer plus a compensating layer for the thermal penetration depth into the uncharred portion of the cross section. The charring depth recommended is shown in Eq. 10 and is based on a compensating layer factor, \( s_0 \). The compensating layer is dependent on the following factors:

- Number of CLT plies
- Overall member thickness
- Stress orientation of fire-exposed side
- Thermal penetration temperature gradient
where:
\[ d_{\text{char, } n/0} = \text{notional or one-dimensional charring depth} \]
\[ k_0 = \frac{1}{\alpha} \text{for unprotected members. Increases linearly from 0 to 1 then remains constant.} \]
\[ s_0 = \text{compensating layer} \]

Char and ply fall off are calculated the same manner as in the EN1995-1-2 and NDS methods. Each of the methods described above accounts for structural deterioration of timber due to fire through the use of a charring method. Two of methods, NDS and SP, accounts for the thermal penetration depth through the use of a compensating factor and assume that failure of the bond line of CLT occurs at 300°C.

**CLT COMPOSITE ACTION MECHANICS**

Both the design of CLT for ambient and fire conditions consider the bond line to never fail until the char layer (300°C isotherm) has reached the bond line. Since timber has no strength above 300°C, the assumption of these methods is that the strength of the glue is adequate enough for failure to occur in the timber and not in the bond line. Bond line failure of CLT is a failure of the engineered mass timber products overall design. Failure of CLT should occur in the weakest portion, namely, the timber.

In order to properly understand the mechanics behind CLT ply interaction and the role the glue plays in the composite action, the interfacial shear \((\tau(x))\) and normal stresses \((\sigma(x))\) need to be understood. Fig. 2 shows the breakdown of the forces between two plies and the adhesive layer between them.

As shown in Fig. 2, the adhesive needs to resist both shear and normal stresses and based on the assumptions from the charring models the glue should resist all stresses below 300°C. Current research shows that this assumption may not be entirely accurate. Two studies were conducted on the shear strength of popular adhesives used to bond CLT. Frangi, Fontana et al. (2004) performed shear tests on glue laminated timber at temperature ranging from 20 to 170°C. Resorcinol-formaldehyde (R-F), one-component polyurethane (1K-PUR) and epoxy...
were used. The blocks heated in an oven to the desired temperature and loaded until failure. The studied revealed that the shear strength of the varied significantly even among the same type of glue and that the shear strength reduced to between 25-75% of the ambient strength. Table 1 shows the temperature at which cohesion failure dominated. The second study was conducted by Clauß, Josca et al. (2011) on the thermal stability of adhesive under shearing loads at temperatures up to 220°C. The conclusion from this study were same as Frangi, Fontana et al. (2004).

Table 1: Temperature of Cohesion Failure (Frangi, Fontana et al. 2004)

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Temperature</th>
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</thead>
<tbody>
<tr>
<td>Kaurat 460 (R-F)</td>
<td>&gt;170°C</td>
</tr>
<tr>
<td>Kauranat 970 (1K-PUR)</td>
<td>180-190°C</td>
</tr>
<tr>
<td>Balcotan 107 TR (1K-PUR)</td>
<td>50-60°C</td>
</tr>
<tr>
<td>Balcotan 60 190(1K-PUR)</td>
<td>190-200°C</td>
</tr>
<tr>
<td>Purbond HB 110(1K-PUR)</td>
<td>60-70°C</td>
</tr>
<tr>
<td>Purbond VN 1033(1K-PUR)</td>
<td>150-160°C</td>
</tr>
<tr>
<td>Araldite AW 136 H (epoxy)</td>
<td>50-60°C</td>
</tr>
</tbody>
</table>

Based on these tests and the force diagram in Fig.2, the importance of the adhesive is clearly demonstrated. Not only will the CLT failure be predominately in the adhesive above approximately 150°C but also the adhesive loses significant strength above 100°C. As the temperature increases, the adhesive will slip and deform and the overall CLT section will have greater deflection. Failure of the section by delamination will be gradual and not sudden. Failure of plies will occur before visual fall off. Several studies have noted fall off in furnace tests on CLT. Craft, Desjardins et al. (2012) conducted vertically oriented CLT tests and noted delamination when the thermocouples at the bond line measured 300°C. Osborne, Dagenals et al. (2012) had several tests exhibit delamination. The temperatures at the bond lines reached 200°C. This was repeated and confirmed by Aguanno (2013). These tests all relied on visual observations to detect delamination and comparisons with thermocouple data.

DISCUSSION

The CLT failure mode of delamination has been identified which current design models do not account. As the thickness of the thermal penetration depth has been measured between 25 to 50 mm (Frangi and Fontana 2003) multiple bond lines of CLT could be above ambient temperatures as the char line progresses through a structural member. The shear and normal strength of the adhesive is an integral part of the composite action design of CLT and they both deteriorate at temperatures above ambient. Complete cohesion failure of the adhesive is between 70°C and 190°C. The extent delamination affects the structural mechanics of CLT has yet to be studied in depth, and proper quantification is necessary to gain an understanding of this failure mode.

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REFERENCES


