Background

- Fire safety provisions are set forth in the International Building Code (IBC).

- Types of construction (IBC, Chapter 6)
  - Type III
    - Interior elements can be of combustible materials
    - Exterior walls are to be non-combustible materials
    - Fire-resistance rating requirements per Table 601
  - Type IV
    - Heavy timber construction (massive wood elements)
    - No fire-resistance rating requirements (except exterior walls)
  - Type V
    - Combustible elements can be used throughout
    - Fire-resistance rating requirements per Table 601

National Design Specifications (Chapter 16) provides a mechanics-based design method for exposed wood members exposed to fire
- Applicable to lumber, glued-laminated timber, poles & piles and structural composite lumber
- For fire-resistance duration up to 2 hours, when required

Cross-laminated timber has an inherent fire-resistance due to its “massive” cross-section

How can we adapt NDS provisions to CLT?

Objectives

- Understand the concept of “fire-resistance”
- Understand cross-laminated timber (CLT) behaviour exposed to fire
- Evaluate the fire-resistance of CLT assemblies
Outline

- Fire-Resistance Test Method (ASTM E119)
- National Design Specifications – Chapter 16
- FPInnovations/NRCC Fire Test Program
  - Charring rate and char depth
  - Adhesive performance
- Application of NDS to CLT
  - Modified char depth calculation procedure
- Conclusion

Fire-Resistance Test Method (ASTM E119)

- What is fire-resistance???
  - Ability of a material, product or assembly to confine a fire or to continue to perform a given structural function, or both.
  - It is NOT a “combustibility” test (e.g. ASTM E136), but rather a “fire performance” test

- What is fire-resistance rating???
  - A measure of the elapse time during which material, product or assembly continues to exhibit fire-resistance under specified exposure conditions.
  - Typically expressed in terms of hours or fraction of hours—
    - 45-min. (¾-hr.)
    - 60-min. (1-hr.)
    - 120 min. (2-hrs.)

Most common standard fire tests (time-temperature curves) are:

- ASTM E119 (USA)
- ULC S101 (Canada)
- ISO 834 (International)
Standard fire-resistance test evaluation criteria

- **Mechanical resistance (R)**
  - Ability of a structural assembly or component to **carry the loads** for the entire fire exposure duration

- **Integrity (E)**
  - Ability of a separating building element to **limit the passage of flames and hot gases** on the unexposed side
Fire-Resistance Test Method (ASTM E119)

- Standard fire-resistance test evaluation criteria
  - **Insulation (I)**
    - Ability of a separating building element to limit temperature rise of the unexposed side under specific limits
      - $\Delta T \leq 250^\circ F$ (average) or
      - $\Delta T \leq 325^\circ F$ (max. of any points)

Column
Height $\leq 12\"-5\"$ (3,81 m)

Floor/Ceiling
16' x 13'
(4,87 x 3,96 m)

Source: NRC-IRC (www.nrc-cnrc.gc.ca)
Fire-Resistance Test Method (ASTM E119)

Wall/Partition
12' x 10'
(3.66 x 3.05 m)

Source: NRC-IRC (www.nrc-cnrc.gc.ca)
Fire-Resistance Test Method (ASTM E119)

Outline

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- Conclusion

National Design Specifications (Chap. 16)

- Mechanics-based design method for exposed wood members exposed to fire
  - Applicable to lumber, glued-laminated timber, poles & piles and structural composite lumber
  - For fire-resistance duration up to 2 hours
  - Using Allowable Stress Design (ASD) procedures
  - Standard notional charring rate ($\beta_n$) of 1 1/2 in./hr.
  - Zero-strength layer multiplier of 1.2
  - Member strength properties adjusted to mean values
  - Using NDS behavioral design equations
  - Recognized in IBC (§721.1)

National Design Specifications (Chap. 16)

- Charring = fundamental process
  - Char layer (burned wood) forms around the element
  - Provides “insulation” protecting inner core against heat effect
  - Defined as the distance between the outer face and the char line interface (isotherm 550°F (300°C))
  - Presume to provide no strength or stiffness...but inner core remains at full design strength and stiffness

- Effective charring rate ($\beta_{\text{eff}}$) as a function of time ($t$)

$$a_{\text{char}} = \frac{\beta_{\text{in}}}{t^{0.187}} t$$

$$= \beta_{\text{eff}} t^{0.813}$$

<table>
<thead>
<tr>
<th>Required Fire Resistance</th>
<th>Effective Charring Rate, $b_{\text{eff}}$ (in/hr)</th>
<th>Visual Char Layer Thickness (in)</th>
<th>Zero-strength Layer (in)</th>
<th>Effective Char Layer Thickness, $b_{\text{eff}}$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 min (¾-h)</td>
<td>1.90</td>
<td>1.19</td>
<td>0.24</td>
<td>1.42</td>
</tr>
<tr>
<td>60 min (1-h)</td>
<td>1.80</td>
<td>1.50</td>
<td>0.30</td>
<td>1.80</td>
</tr>
<tr>
<td>90 min (1½-h)</td>
<td>1.67</td>
<td>2.09</td>
<td>0.42</td>
<td>2.50</td>
</tr>
<tr>
<td>120 min (2-h)</td>
<td>1.58</td>
<td>2.64</td>
<td>0.53</td>
<td>3.16</td>
</tr>
</tbody>
</table>

$$\beta_{\text{in}} t^{0.813} = 0.2 \beta_{\text{in}} t^{0.813}$$

$$a_{\text{char}} = \beta_{\text{eff}} t = 1.2 \beta_{\text{in}} t^{0.813}$$

$$\beta_{\text{eff}} = 1.2 \beta_{\text{in}} / t^{0.187}$$

- Reduced cross-section as a function of time ($t$)

- Member strength and capacity adjustments
  - Design values adjusted to mean values
    (5th percentile $\rightarrow$ 50th)

<table>
<thead>
<tr>
<th>Strength</th>
<th>Strength Adjustment Factor ($K$)</th>
<th>Size Factor ($C_r$)</th>
<th>Volume Factor ($C_v$)</th>
<th>Flat Use Factor ($C_u$)</th>
<th>Beam Stability Factor ($C_b$)</th>
<th>Column Stability Factor ($C_c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending ($F_{b}$)</td>
<td>2.85</td>
<td>$C_r$</td>
<td>$C_v$</td>
<td>$C_u$</td>
<td>$C_b$</td>
<td>$C_c$</td>
</tr>
<tr>
<td>Tensile ($F_{t}$)</td>
<td>2.85</td>
<td>$C_r$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Axial Compression ($F_{a}$)</td>
<td>2.58</td>
<td>$C_r$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$C_c$</td>
</tr>
<tr>
<td>Beam Buckling ($F_{b}$)</td>
<td>2.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Column Buckling ($F_{c}$)</td>
<td>2.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
National Design Specifications (Chap. 16)

Examples of NDS Behavioral Design Equations

<table>
<thead>
<tr>
<th>Structural Design</th>
<th>Normal (ambient) conditions</th>
<th>Fire conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>$D + l \leq F_{\text{lb}}$</td>
<td>$D + l \leq 2.85 \times F_{\text{lb}}$</td>
</tr>
<tr>
<td></td>
<td>$S_{\text{ls}}$ $C_{\text{ILs}}$ $C_{\text{IM}}$ $C_{\text{lt}}$</td>
<td>$S_{\text{lf}}$ $C_{\text{ILf}}$ $C_{\text{IM}}$ $C_{\text{lt}}$</td>
</tr>
<tr>
<td>Axial Compression</td>
<td>$D + l \leq F_{\text{lc}}$</td>
<td>$D + l \leq 2.58 \times F_{\text{lc}}$</td>
</tr>
<tr>
<td></td>
<td>$S_{\text{lp}}$ $C_{\text{ILp}}$ $C_{\text{IM}}$ $C_{\text{lt}}$</td>
<td>$S_{\text{lp}}$ $C_{\text{ILp}}$ $C_{\text{IM}}$ $C_{\text{lt}}$</td>
</tr>
</tbody>
</table>

NDS design procedures seem applicable to CLT, but...
- It addresses only the structural requirements of timber elements subjected to bending, compression and tension — CLT is a separating element, so needs to respect all 3 criteria (R, E, I)
- Are the NDS behavioral design equations suitable to CLT?
- Is the nonlinear effective charring rate valid for CLT?
- Does the adhesive used exhibit delamination when exposed to fire?
- Can Type X gypsum board delay time to charring of CLT?

Outline

- Fire-Resistance Test Method (ASTM E119)
- National Design Specifications – Chapter 16
- FPInnovations/NRCC Fire Test Program
  - Charring rate and char depth
  - Adhesive performance
- Application of NDS to CLT
  - Modified char depth calculation procedure
- Conclusion

FPInnovations/NRCC Fire Test Program

- Eight (8) full-scale fire tests conducted following ULC S101 time-temperature curve
  - Conducted at NRC facility in Ottawa (Ont.)
  - Joint FPInnovations/NRCC Test report and TechNote available

Objectives

1. Quantify the charring rate
2. Evaluate the fire resistance of CLT assemblies
3. Develop a simple analytical model to predict CLT fire resistance
FPInnovations/NRCC Fire Test Program

- Specimens manufactured conforming to ANSI/APA PRG-320 standard
  - 3-, 5- and 7-plys CLT
  - SPF No1/No2, No3 and MSR lumber
  - Loaded specimens (based on strength or serviceability)
    * Values shown exclude the specimen self-weight (dead load)

- Adhesive
  - Polyurethane (PUR)
    - ANSI/APA PRG-320 approved

- Gypsum Board
  - 1 layer of 5/8" (15.9 mm) Type X
  - 2 layers of 1/2" (12.7 mm) Type X

Instrumentation (typ.)

<table>
<thead>
<tr>
<th># of Piles</th>
<th>Lumbar Grade in Major Strength Direction</th>
<th>Thickness in (mm)</th>
<th>Gypsum Board Protection in (mm)</th>
<th>Superimposed Load</th>
<th>Load Ratio (ASD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>MSR 1650f-1.5E</td>
<td>4.49 (14)</td>
<td>2 x ½ (12.7)</td>
<td>22818 lb/ft (333 kN/m)</td>
<td>58%</td>
</tr>
<tr>
<td>5</td>
<td>MSR 1950f-1.7E</td>
<td>6.69 (25)</td>
<td>Unprotected</td>
<td>22818 lb/ft (333 kN/m)</td>
<td>29%</td>
</tr>
<tr>
<td>5</td>
<td>No.1/No.2</td>
<td>4.13 (105)</td>
<td>Unprotected</td>
<td>4934 lb/ft (72 kN/m)</td>
<td>23%</td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>MSR 1650f-1.5E</td>
<td>4.49 (14)</td>
<td>2 x ½ (12.7)</td>
<td>56 psf (2.7 kPa)</td>
<td>46%</td>
</tr>
<tr>
<td>5</td>
<td>MSR 1950f-1.7E</td>
<td>6.69 (25)</td>
<td>Unprotected</td>
<td>246 psf (11.8 kPa)</td>
<td>75%</td>
</tr>
<tr>
<td>5</td>
<td>No.1/No.2</td>
<td>4.13 (105)</td>
<td>1 x ½ (15.5)</td>
<td>50 psf (2.4 kPa)</td>
<td>90%</td>
</tr>
<tr>
<td>7</td>
<td>No.1/No.2</td>
<td>9.65 (245)</td>
<td>Unprotected</td>
<td>305 psf (14.6 kPa)</td>
<td>119%</td>
</tr>
</tbody>
</table>
### Charring Rates from Test Data (in./hr)

<table>
<thead>
<tr>
<th>Location</th>
<th>TCS 1</th>
<th>TCS 1-2</th>
<th>TCS 2</th>
<th>TCS 2-3</th>
<th>TCS 3</th>
<th>TCS 3-4</th>
<th>Overall From Test Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Walls</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.49” (3 x 38 mm)</td>
<td>0.97</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.97</td>
</tr>
<tr>
<td>6.89” (5 x 35 mm)</td>
<td>1.56</td>
<td>1.32</td>
<td>2.31</td>
<td>1.30</td>
<td>-</td>
<td>-</td>
<td>1.54</td>
</tr>
<tr>
<td>4.13” (5 x 21 mm)</td>
<td>1.25</td>
<td>2.36</td>
<td>2.24</td>
<td>2.36</td>
<td>-</td>
<td>-</td>
<td>1.89</td>
</tr>
<tr>
<td>4.49” (3 x 38 mm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6.89” (5 x 35 mm)</td>
<td>1.23</td>
<td>1.39</td>
<td>2.17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.51</td>
</tr>
<tr>
<td>4.13” (3 x 35 mm)</td>
<td>1.02</td>
<td>2.41</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.42</td>
</tr>
<tr>
<td>6.89” (5 x 35 mm)</td>
<td>1.30</td>
<td>1.61</td>
<td>2.65</td>
<td>2.13</td>
<td>-</td>
<td>-</td>
<td>1.77</td>
</tr>
<tr>
<td>9.65” (7 x 35 mm)</td>
<td>0.97</td>
<td>1.75</td>
<td>2.24</td>
<td>1.75</td>
<td>1.32</td>
<td>1.89</td>
<td>1.54</td>
</tr>
</tbody>
</table>

### Adhesive Performance

- CLT panels were manufactured with a structural polyurethane (PUR) adhesive conforming to ANSI/APA PRG-320 standard.
- Small pieces of the charred layer were observed to fall off during the fire-resistance tests when the glue lamination interface reached ±550°F (300°C).
- Thermal protection from the charred layer no longer in place, thus accelerating the effective charring rate when approaching the glue laminations.
- Thinner laminations (< 1¾”) seem to char faster (±10%).
- Need to be accounted for in the char depth calculation.
Outline

- Fire-Resistance Test Method (ASTM E119)
- National Design Specifications – Chapter 16
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  - Adhesive performance
- Application of NDS to CLT
  - Modified char depth calculation procedure
- Conclusion

Application of NDS to CLT

- US Edition of the CLT Handbook – Chapter 8
  - Authors
    - Christian Dagenais, Eng., M.Sc. - FPInnovations
    - Robert H. White, Ph.D. – USDA Forest Products Laboratory
    - Kuma Sumathipala, Ph.D. – American Wood Council
  - Peer-reviewers
    - Sam Francis, M.En.Sc.
      American Wood Council
      Churchill Engineering Inc.
    - Joe McElvaney
      City of Phoenix
    - Prof. Dr. Andrea Frangi
      ETH Zurich Institute of Str. Eng.

- Calculation procedure adapted to CLT assemblies
  - Mechanics-based method
  - Allowable Stress Design (ASD) procedures
  - Standard notional charring rate ($\beta_n$) of 1.5 in./hr.
  - Nonlinear stepped charring rate adjustment
  - Zero-strength layer multiplier of 1.2
  - Member strength properties adjusted to mean values
  - Using NDS behavioral design equations
Application of NDS to CLT

- Calculation procedure adapted to CLT assemblies
  "STEPPED MODEL": reset the nonlinear charring rate at every glue lamination interface of the CLT panel

  Step 1: Calculation of lamination fall-off time ($t_{fo}$)
  
  $$ t_{fo} = (\frac{h_{lam}}{\beta_{ln}})^{1.23} $$

  Calculate number of layers that may fall-off ($n_{lam}$)
  
  $$ n_{lam} = INT\left(\frac{t}{t_{fo}}\right) $$

  Step 2: Calculation of the effective char depth
  
  $$ a_{char} = 1.2 \left( n_{lam} \cdot h_{lam} + \beta_{ln} \cdot (t - (n_{lam} \cdot t_{fo}))^{0.813} \right) $$

  Step 3: Determination of effective residual cross-section

  Step 4: Find location of neutral axis and section properties

  Step 5: Calculation of structural resistance
Application of NDS to CLT

- **Structural criteria (R)**
  
  **Step 1a:** Calculation of lamination fall-off time ($t_{fo}$)

  
  **Step 1b:** Calculate number of layers that may fall-off ($n_{lam}$)

  
  **Step 2:** Calculation of the effective char depth

  $a_{char} = 1.2 \cdot n_{ilam} \cdot h_{ilam} + \beta \cdot n \cdot (t - (n_{ilam} \cdot t_{fo})) / 0.813$

  
  **Step 3:** Determination of effective residual cross-section

  $h_{fire} = h - a_{char}$
Application of NDS to CLT

- **Structural criteria (R)**

Step 4: Find location of neutral axis and section properties ($A_{eff}$, $S_{eff}$ and $I_{eff}$)

Walls are susceptible to buckling ($P-\Delta$ effects)

\[(P/P^0)\Delta + M + P\Delta (1 + 0.234 P/PlcE) / Plb \leq 1 \]

- **Integrity criteria (E)**

\[ tIE = 0.35H/\beta in \]

Note: The diagrams illustrate the structural and integrity criteria with relevant calculations and observations.
Application of NDS to CLT

- Insulation criteria (I)

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Failure time (min)</th>
<th>Effective Residual Thickness (in)</th>
<th>Temperature Furnace (°F)</th>
<th>Temperature Unexposed surface (°F)</th>
<th>Temperature Initial condition (°F)</th>
<th>Temperature Rise on Unexposed Surface (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall 1</td>
<td>196</td>
<td>3.82</td>
<td>1817</td>
<td>75</td>
<td>73</td>
<td>2</td>
</tr>
<tr>
<td>Wall 2</td>
<td>113</td>
<td>3.62</td>
<td>1850</td>
<td>70</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Wall 3</td>
<td>57</td>
<td>1.93</td>
<td>1922</td>
<td>86</td>
<td>70</td>
<td>16</td>
</tr>
<tr>
<td>Floor 1</td>
<td>77</td>
<td>4.13</td>
<td>1780</td>
<td>72</td>
<td>73</td>
<td>1</td>
</tr>
<tr>
<td>Floor 2</td>
<td>96</td>
<td>4.13</td>
<td>1800</td>
<td>68</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td>Floor 3</td>
<td>86</td>
<td>2.20</td>
<td>1783</td>
<td>140</td>
<td>72</td>
<td>68</td>
</tr>
<tr>
<td>Floor 4</td>
<td>124</td>
<td>3.50</td>
<td>1843</td>
<td>81</td>
<td>73</td>
<td>8</td>
</tr>
<tr>
<td>Floor 5</td>
<td>178</td>
<td>4.13</td>
<td>1920</td>
<td>86</td>
<td>68</td>
<td>18</td>
</tr>
</tbody>
</table>

* Test was stopped due to equipment safety concerns. Failure was not reached.

Performance of Type X gypsum boards
- Structural model is for exposed CLT up to 2 hours
- Use of Type X gypsum board can allow increasing the fire-resistance by:
  - 30 minutes when 1 layer of ⅝” Type X is used
  - 60 minutes when 2 layers of ⅝” Type X are used

- Gypsum boards shall be directly attached to CLT using:
  - 2¼” Type S drywall screws @ 12” o.c. along the perimeter and throughout
  - Screws shall be placed at least 1½” from the sides of board edge
  - Exposed layer joints shall be taped and coated with joint compound
  - Screw heads of exposed layer shall be covered with joint compound
Outline

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Conclusion

- Fire-resistance is:
  - An important building “performance” attribute
  - NOT related to the “combustibility” of materials
- Cross-laminated timber has an inherent fire-resistance due to its “massive” cross-section
  - Char rate is predictable ($\beta_n$ of $\pm1\frac{1}{2}$ in./hr)
  - Comparisons between the proposed mechanics-based method and the experimental data show good agreement

CLT excellent fire performance facilitates Code acceptance when using “alternative solutions” to traditional non-combustible structural elements

FYI: Heavy timber and glued-laminated timber behaves the same way in fire conditions...
- Predictable charring rates
- Reduced cross-section
- Concealed connections is recommended
- Structural engineering is required for structural fire design

Special Thanks

- Industry organizations
- Industry members
  - Julie Frappier, Eng. of Nordic Engineered Wood
  - Andre Morf of Structurlam
  - Dr. Bénichou of National Research Council Canada
- All peer-reviewers
- ...and all of you for attending and listening!
Fire-Performance of Cross-Laminated Timber
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