Quality control of X-lam:
Validity of bending tests on strip-shaped specimens to derive strength and stiffness properties

René Steiger
EMPA, Wood Laboratory
Dübendorf, Switzerland

Arne Gülzow
Carbo-Link GmbH
Fehraltorf, Switzerland

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Introduction
Cross-laminated timber (CLT): The product and …
… its application
Design of CLT when used as plate

- **Needs:**
  - Verification of ultimate and serviceability limit states
  - Strength properties: bending and shear strength
  - Stiffness properties: MOE, shear moduli

- **Key parameters:**
  - Stiffness properties

- **Regulations on testing (evaluation of performance characteristics):**
  - EN 789:
    - 4-point bending tests of 300 mm wide strip-shaped specimens
    - 1 strip per plate and grain direction of the face layers
How to derive bending strength and stiffness of CLT?

- Bending strength and stiffness
  - Compound theory
    - Basis: mechanical properties of the layers
    - Reliable strength grading of the raw material is needed
  - Bending tests of strip-shaped cut offs
    - Width = 300 ± 5 mm, span = 300 mm + 32 · t (t = nominal thickness)
    - Small samples or rather single specimens in production control
    - Large samples needed to derive characteristic values

- Bending stiffness
  - Modal analysis

Validity of bending tests of strip-shaped specimens?
Tested material
CLT supplied by 2 producers (A, B)

<table>
<thead>
<tr>
<th>Series</th>
<th>Length $^1$ x Width $^1$ [m]</th>
<th>$t$ [mm]</th>
<th>Lay-up [mm]</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.50 x 2.50</td>
<td>70</td>
<td>Product A and B: 10/50/10</td>
<td>9 x A, 9 x B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product A and B: 25/20/25</td>
<td>9 x A, 9 x B</td>
</tr>
<tr>
<td>2</td>
<td>2.50 x 2.50</td>
<td>110</td>
<td>Product A: 35/40/35</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product B: 20/70/20</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>4.00 x 2.50</td>
<td>80</td>
<td>Product A: 25/30/25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product B: 15/50/15</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>110</td>
<td>Product B: 15/15/20/15/15</td>
<td>3</td>
</tr>
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<td></td>
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<td>Product A: 35/40/35</td>
<td>3</td>
</tr>
</tbody>
</table>

$^1$ parallel to the grain direction of the face layers

3 - 5 layers, $t = 70 - 110$ mm    42 panels

Norway spruce lamellas (*picea abies Karst.*)
Differences in products A and B

Product A
- Face layers: C24, $b = 70$ mm
- Inner layers: C20, $b = 100 – 150$ mm, grooved, no lateral adhesive bond
- 1-component PUR

Product B
- Lay up 10/50/10 mm
- Lay up 25/20/25 mm
- All layers: C24, $b = 25$ mm
- MUF
- Better homogenization
Cutting scheme

Series 1 – CLT panels

- Product A
  - Width of strips = 100 mm
  - $n = 5 - 6$
  - 5 - 6 strips of 100 mm width in both directions

Series 2 – CLT panels

- Product B
  - Width of strips = 100 mm
  - $n = 5 - 6$

- Products A and B
  - $n = 1$
  - 1 strip of 300 mm width in both directions

- Products A and B
  - 300 mm
Test methods
Bending stiffness assessed by modal analysis

Theoretical modal analysis

\[ \int \varepsilon^T \cdot C \cdot \varepsilon \cdot dV + \int \delta u^T \cdot \rho \cdot \ddot{u} \cdot dV = 0 \]

\[ \text{frequency}_{\text{theo}}, \text{eigenmode}_{\text{theo}} \]

Experimental modal analysis

\[ \text{frequency}_{\text{exp}}, \text{eigenmode}_{\text{exp}} \]

Optimisation:

\[ \min(\sum (\text{freq}_{\text{exp}} - \text{freq}(C_{ij})_{\text{theo}})^2) \rightarrow C_{ij} \]
Verification by static bending tests

Single load in centre of the plate

Displacement transducers
Check of the elastic lines

Bending deformation parallel to the grain direction of the face layers

<table>
<thead>
<tr>
<th>Plattenlänge [cm]</th>
<th>Durchbiegung [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kN Experiment</td>
<td>14.98 mm</td>
</tr>
<tr>
<td>20 kN Simulation</td>
<td>14.89 mm</td>
</tr>
</tbody>
</table>

Deflection [mm]

0 50 100 150 200 250 300 350 400

- 20 kN Experiment
- 20 kN Simulation
Load configurations
Bending tests of strip-shaped specimens: series 1

- 4-point bending test according to EN 789
- Width of the specimens = 100 mm (instead of 300 mm)
- Span = 1100 mm
- MOE: measurement of deformations: 10% - 40% $f_u$
- Loading rate: failure after $300 \pm 120$ sec
- $E_{11}, E_{22}, f_{m,1}, f_{m,2}$, failure mode
Bending tests of strip-shaped specimens: series 2

- Centre point bending according to EN 408
- Variable span method \( h/\ell = 0.0037 – 0.035 \)
- \( E_{11}, E_{22}, G_{13}, G_{23} \)
- Measurement of deformations: 10% - 40% \( f_u \)
- Loading rate: slightly above EN 408 limit
- Strips with grooves tested twice with changing orientation of tension / compression edge
Results
Series 1 – CLT panels

- **Product A**
  - Width of strips = 100 mm
  - \( n = 5 \text{ - } 6 \)
- **Product B**
  - Width of strips = 100 mm
  - \( n = 2 \text{ - } 3 \)
Bending strength of plates vs. strips (series 1)

- Panel tests of product A (n = 12)
- Panel tests of product B (n = 12)
- Strip-shaped tests of product A (n = 70)
- Strip-shaped tests of product B (n = 78)

COV_{A,B} = 17%
COV_A = 16%
COV_B = 10%

Bending strength f_m [N/mm²]

+ 40%
+ 50%
Failure modes: strip shaped specimens

- 129 bending failures, 42.6%
- 58 local defects, 19.1%
- 19 mixed failures, 6.3%
- 97 (rolling) shear failures, 32%

\[ n_{\text{tot}} = 303 \]
Failure modes: gross CLT plates

22 bending failures, 91.6%
1 punching, 4.2%
1 shear failure, 4.2%

\[ n_{\text{tot}} = 24 \]
Example: $E_{11}$ of panels with lay up 10/50/10 mm

- High COV due to big variations in the raw material
- $E_{11}$ derived by modal analysis on whole plate and mean $E_{11}$ from testing of strips match quite well
Normal probability plot $E_{11}$ of panels 10/50/10

- Mean values meet quite well for both products
- Standard deviations do not
Normal probability plot $E_{22}$ of panels 10/50/10

- Good agreement of mean values along product A
- Again differences in standard deviation
Series 2

Series 2 – CLT panels

Products A and B

300 mm

n = 1

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Comparison of MOE (modal analysis and static test)

- Overall independent from product: differences = small to moderate
- Good agreement for parameter $E_{22}$
- Differences also result from different speed of action!
Comparison of shear moduli (modal analysis and static test)

- Good agreement for parameter $G_{13}$
- Some big differences in $G_{23,\text{mod}}$ and $G_{23,\text{stat}}$ → Wherefrom?
Shear moduli are influenced by local non-homogeneities

- Knots
- Pitch pockets
- Deviated grain
- Grooves

Defects partly affected whole layers, resulting in a severe reduction of the stiffness of the layers.
Conclusions
Conclusions (1)

- Big variations of bending strength and stiffness within single CLT panels
  - Deriving respective properties from bending tests of few or single strip-shaped specimens is not possible.

- Increased accuracy of the test results when:
  - Performing bending tests of strip-shaped specimens exactly according to EN 789, i.e. with a width of 300 mm
  - Increasing sample size

- Variation of the stiffness properties depends on the degree of homogenization of the actual CLT panel product
  - Small components (lamelllas) → less variation in mechanical properties
  - Strength grading of the raw material needed
  - Local non-homogeneities (knots, pitch pockets, deviated grain, not adhesively bonded contacts, cuts, grooves, cracks) are of bigger influence with strip-shaped specimens than with gross panels
Conclusions (2)

- Shear moduli influenced by:
  - Middle layer parts not adhesively bonded at their lateral sides
  - Cuts and grooves (aiming at reducing the deformations of the CLT panel in case of changing moisture)

- Failure modes:
  - Strip-shaped specimens:
    - (Rolling) shear failures occur frequently
  - Gross CLT:
    - Bending failure was dominating
    - Beware of punching esp. with thin plates and products with grooves and layers adhesively not bonded at lateral sides!

- Estimation of stiffness properties of CLT:
  - Modal analysis is a good alternative to the compound theory if raw material is not strength graded or its mechanical properties are not known with sufficient precision
Acknowledgement

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Experimentals

- Empa, Structural Engineering Research Lab
- ETH Zurich, Institute for Building Materials, Wood Physics
Discussion
EN 408 variable span method

\[ K_I = \frac{1/E_{m,app}}{(h/\ell)^2} \]

\[ 1/E_{m,\ell} \]

\[ G_{13}, G_{23} \]

\[ E_{11}, E_{22} \]
$E_{22}$ of panels with lay up 10/50/10 mm
$E_{11}$ and $E_{22}$ of panels with lay up 25/20/25 mm

![Graphs showing $E_{11}$ and $E_{22}$ values for panels A and B, with different markers indicating modal analysis, mean values, maximum values, and minimum values.](EMPA.png)