Seismic response of wood structures

From material damage to tall buildings

Dr Christian Málaga-Chuquitaye
Outline

• Introduction
• Damage (plasticity) model for wood
• Experimental response of timber panels
• Seismic response of timber buildings
• Concluding remarks
• Luis Fernando Sirumbal Zapata

• Juliet Kernohan

• Cagatay Demirci
Global challenge of urbanization

- People is moving to cities
- The urban population of the world has grown from 746 million (in 1950) to 3.9 billion in 2014
- 2.5 billion people will move to cities by 2050
- That means we need to build a 1-million city each week!
The magnitude of the problem (size, resources, time) is huge!

... and we need to tackle global warming (reduce CO₂ emissions)
... and we need to consider that more than half of the world’s megacities are actually in earthquake prone regions

As the global population grows and becomes increasingly urban, current construction practices are unsustainable. Concrete and steel are energy-intensive materials and our industry is a main contributor to global carbon dioxide emissions.
... we cannot continue building as we are, can we?
Photographs from Fast, Light and Green by MetzaWood
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- Introduction
- Coupled damage-plasticity model for wood
- Experimental response of timber panels
- Seismic response of timber buildings
- Concluding remarks
Compression perpendicular

Compression parallel

Tension
- The performance of timber structures is governed by the nonlinear response in the connection zones (high deformation levels and stress concentrations).

- These zones are also susceptible to significant load-reversals during the service life of structures, especially during extreme load scenarios such as earthquakes.
Constitutive modelling of wood

- Kharouf et al. (2005) – 2D elastic-plastic orthotropic model for wood using Hill’s yield criterion
- Xu et al. (2014) – anisotropic plasticity (Hill’s) and simplified damage (direct reduction of elastic modulus in the 3 directions)
- Sandhaas et al. (2014) – 8 types of ductile and brittle failure modes, each one of them associated with a different failure criterion, Damage only
- Khelifa et al. (2016) – damage plasticity model but no different input strengths for tension and compression and uses a single Hill’s surface for both plasticity and damage criteria. Not suitable for our purposes either
Strain-based isotropic damage model for timber (tension & shear)

- Brittle failure due to tension and shear stresses generates voids and micro-cracks in the timber matrix which not only lead to a sudden reduction in strength, but also cause a gradual degradation of its mechanical properties (including stiffness)
- Two key concepts (CDM):
  - Effective stress
  - Hypothesis of strain equivalence: strain associated with the Cauchy stress in damage state is equivalent to the strain associated with effective stress in the un-damage state
Effective stress

- The stress acting in the reduced un-damaged net surface area of the material (not considering the micro-cracks and voids)
- The effective stress tensor is transformed into the Cauchy stress tensor by means of a fourth-order tensor which is a function of the damage tensor

\[ \sigma = M(D) : \bar{\sigma} \]

Anisotropic damage is considered by assigning different values to the damage variable components of D (2\textsuperscript{nd} or 4\textsuperscript{th} order tensor)
Why isotropic damage model for timber (tension & shear)?

- The evolution laws for the damage variables in each orthotropic direction are not known and difficult to obtain experimentally.
- The Strain Equivalence hypothesis is not valid for anisotropic damage, and therefore, it is not possible to obtain a mechanically consistent anisotropic damage tensor without losing the symmetry of either the Cauchy or the effective stress tensors.
Spectral decomposition of the effective stress tensor

\[ \bar{\sigma}^+ = \sum_{i=1}^{3} (\bar{\sigma}_i) p_i \otimes p_i \]

\[ \bar{\sigma}^- = \bar{\sigma} - \bar{\sigma}^+ \]

- Independent damage mechanisms for tension and compression
- Enables indirect modelling of opening and closing of cracks
Isotropic damage

\[ \sigma = (1 - \omega^+)\bar{\sigma}^+ + (1 - \omega^-)\bar{\sigma}^- \]

- Scalar isotropic damage relationship is reformulated in terms of tensile and compressive components.

\[ f_d^{\pm}(\bar{\sigma}^\pm, r^\pm) = \bar{\tau}^\pm - r^\pm \]

- The initiation of the damage evolution process is determined by the damage criteria function:

\[ \bar{\tau}^\pm = \sqrt{\frac{1}{2} \bar{\sigma}^{\pm T} H^\pm \bar{\sigma}^\pm} \]

\[ (f_X^\pm, f_Y^\pm, f_Z^\pm, f_{XY}, f_{YZ}, f_{ZX}) \]
The Damage Evolution Law defines the variation of the damage variable as a function of the threshold variable.

\[
\omega^\pm = g_d^\pm (r^\pm)
\]

\[
g_d^+(r^+) = 1 - \frac{r_0^+}{r^+} \left(1 - n + ne^{-b(r^+-r_0^+)} \right)
\]

- Calibration parameter
- Constant dependent on the mesh size (through the characteristic length)
Damage evolution law - tension

\[ \omega^\pm = g_d^\pm (r^\pm) \]

\[ g_d^+ (r^+) = 1 - \frac{r_0^+}{r_+} \left( 1 - n + ne^{-b(r_+ - r_0^+)} \right) \]

Calibration parameter

Constant dependent on the mesh size (through the characteristic length)
**Damage evolution law - tension**

\[ \omega^\pm = g^\pm_d (r^\pm) \]

\[ g^+_d (r^+) = 1 - \frac{r_0^+}{r^+} \left( 1 - n + n e^{-b(r^+-r_0^+)} \right) \]

- **Calibration parameter**
- **Constant dependent on the mesh size (through the characteristic length)**

\[ \sigma^+ = \frac{r^+}{r_0} f_{\text{max}} \left[ 1 - g^+_d (r^+) \right] \]
Damage evolution law - compression

\[ \omega^\pm = g_d^\pm (r^\pm) \]

\[ g_d^- (r^-) = \beta \times \left(1 - \frac{r_0}{r^-}\right)^m \]

Calibration parameter

(b) Damage variable, \( \omega^- \).
Damage model

• Damage criteria function

\[ f_d^\pm (\bar{\sigma}^\pm, r^\pm) = \bar{\tau}^\pm - r^\pm \]

• Damage evolution law

\[ \omega^\pm = g_d^\pm (r^\pm) \]

• Loading-unloading conditions

\[ f_d^\pm \leq 0; \quad \dot{r}^\pm \geq 0; \quad \dot{r}^\pm f_d^\pm = 0 \]
Model verification

Length: 1.5 m
Cross section of 130 mm 152 mm
Steel plates: 12 mm thick
Spacing between the two bolts: 76 mm
Length: of 1.5 m
Cross section of 130 mm 152 mm
Steel plates: 12 mm thick
Spacing between the two bolts 76 mm
Other ways of modelling damage

- Foundation modelling approach – embedment tests PARALLEL
Other ways of modelling damage

- Foundation modelling approach – embedment tests PERPENDICULAR
Cyclic response of post-tensioned timber frames
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An alternative way to tackle wood’s anisotropy

- By engineering it out!
- Using timber to reinforce timber (cross-laminated-timber - CLT)
- Large in-plane stiffness
- Has enabled the pursuit of the “tall timber” paradigm
Lateral deformation modes of timber CLT walls

- Two fundamental failure mechanisms have been observed in CLT shear walls
- Dearth of codified guidance regarding their design
Summary of tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions H x L [m]</strong></td>
<td>1.8x1.8</td>
<td>1.8x1.8</td>
<td>1.8x2.5</td>
<td>1.8x2.5</td>
<td>1.8x3.2</td>
<td>1.8x3.2</td>
</tr>
<tr>
<td><strong>Bracket configuration</strong></td>
<td>5 x WB100 brackets</td>
<td>5 x WB100 brackets</td>
<td>5 x WB100 brackets</td>
<td>3 x WB100 brackets + 2 WHT340 hold-downs</td>
<td>6 x WB100 brackets</td>
<td>4 x WB100 brackets + 2 WHT340 hold-downs</td>
</tr>
<tr>
<td><strong>Vertical load [kN/m]</strong></td>
<td>3.3</td>
<td>12</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>
Cyclic protocol (EN 12512)
Failure modes
Hysteretic response – Specimen P3 (all SB, 2.5 m)
Effects of length of panel

- **P1 – 1.8m (C5)**: Force Actuator [kN] range from 70 kN to 130 kN
- **P3 – 2.5m (C5)**

Drift [%]

Force Actuator [kN]

Fmax from 70 kN to 130 kN
Effects of length of panel

Reduction in failure drift from 5.5 to 4.2%

- P3 – 2.5m (C5)
- P1 – 1.8m (C5)
Evolution of shear forces in P4
Maximum normal strain field in P1-SB
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Cyclic response of CLT walls and cores

OpenSees model

Experimental and numerical hysteresis

Experimental and numerical cumulative energy
Dynamic response of CLT buildings

Experiments by Ceccotti et al. (2006; 2013)
Building database

- Storeys: 6, 8, 12, 16, 20
- Vertical joints, m: 0, 1, 2, 3 per 4m
- Behaviour factors q: 2, 2.5, 3, 4
- 1656 real ground-motion records
  (Mw ranging from 5.61 to 7.9 & PGA_{avg} 1 g)
Assessment of seismic drift demands

- 112608 analyses (HPC computer)
- Drift modification factor:
  \[
  \delta_{mod} = \frac{\Delta_{max}}{q \cdot \Delta_{1,roof}}
  \]
- The shaded regions in these figures depict the 95% confidence interval
- (o) and (*) denote the mean and median values within bins
Influence of behaviour factor (8 storey building, m=1)

Influence of number of storeys (q =3)

Influence of panel fragmentation, m (8-storey building)
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Concluding remarks

• Wood is the only construction material that grows with the sun and can play an important role in our efforts to tackle the issue of urbanization under great environmental uncertainties and extreme natural hazards.
• ... BUT we need to make the economic case.
• ... AND, in order to do so, we need to improve the quality of our current response prediction and design tools and methods.
• Well validated numerical models underpinned by carefully conducted experiments are fundamental in developing our understanding of the mechanical response of (wood) structures ultimately leading to greater societal and economic benefits and impact.
References

- [http://www.imperial.ac.uk/emerging-structural-technologies](http://www.imperial.ac.uk/emerging-structural-technologies)
Thank you!

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Emerging Structural Technologies and Design