Validation & Verification of automated non-linear modelling for the seismic response of cross laminated timber structures

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- Paris, 20.03.2018 -
The Big Picture
The Professional use

Import CAD Geom.
Create Model Geometry and Mesh
Perform Linear Analyses
  To determine sections,
  To design for regulatory codes

Perform NON-LINEAR analyses.

Optimization
  Performance-based Design
  Resilience-based Design

All with AUTOMATED Procedures
**Our Strange Friend: Wood**

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### Anisotropy

- $\sigma_{90}$
- $E_{90} \approx E_0 / 30$
- $G_{0(90)} \approx E_0 / 16$
- $G_{90(90)} \approx G_0 / 10$
- $\approx E_0 / 160$

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### CLT Panel

- Composite layout
- Different bending stiffness in the two main directions and planar stability
- Use both as walls and floors

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**Image:** Our Strange Friend Wood
Global Behaviour dominated by Contact and Discrete Connections

Seismic Behaviour
Rocking (rotation) and Sliding for each panel

- Tension-only hold-down
- Monolateral contact
- Shear-only discrete + Friction
Global Non-linear Behaviour

Connectors:
- No Resistance in compression
- Pinching Response in tension/shear

Panels:
- Monolateral contact

Uplift

Link Video: https://www.dropbox.com/s/7y6nezlyewim94d/Deformed_C4-Kobe-082.mp4?dl=0
Modelling Approach
Modelling Approach
Modelling Approach

- Coincident nodes

1st generation model
- LIASON GROUP on DX, DY, DZ
- Contact face material properties based on connections

2nd generation model
- Contact Zones
- Formulation CONTINUOUS
Connections

Angle Bracket (AB)
K_T_D_L springs with shear stiffness
WC / WFC / FC

K_T_D_L springs
with axial and
shear stiffness
Connections

Hold-down (HD)
K_T_D_L springs with axial stiffness
Connections

HD as two elements in series

Static non-linear analysis
- $K_{T_D_L}$ spring with axial stiffness and kinematic hardening (DIS_ECRO_CINE)
- CABLE element

Dynamic non-linear analysis
- $K_{T_D_L}$ spring with axial stiffness and kinematic hardening (DIS_ECRO_CINE)
- $K_{T_D_L}$ spring with axial stiffness and asymmetric hardening (ECRO_ASYM_LINE)
Sofie Project
Real Scale Test on CLT Structure

Scientific Director: Prof. Ing. Ario Ceccotti

Funded by: Provincia Autonoma di Trento

In collaboration with:

CNR-IVALSA
(Italian National Research Council – Trees and Timber Institute)
The model

- 449 faces (61 CLT panels)
- 204 common edges with contact & friction
- 1543 discrete elements, that represent 9 different types of connectors
- Panels are connected with 211 different connections
The model

All groups and contact zones created automatically
Validation Process

- Linear Elastic Model
- Non-linear with contact without friction
- Non-linear with contact and friction $\mu=0.2$
- Non-linear with contact and friction $\mu=0.4$

**Validation based on:**
- Hysteresis loops
- Time-history of base shear and drift
- Vibration periods

**Subjected to:**
- Kobe JMA motion scaled to 0.15g
- Cyclic Pushover analysis
Linear model

- Base Shear [kN]:
  - Test: +16.8%
  - Model: +34.7%

- Roof Drift [mm]:
  - Test: +115.7%
  - Model: +98.0%
Non-linear model
Contact without friction | $\mu = 0.0$

- Base Shear: +13.3%
- Roof Drift: +40.2%
- +139.0%
- +130.5%
Non-linear model
Contact with friction | $\mu = 0.2$

![Graphs showing base shear and roof drift over time with comparison between test and model results.](aethereng.com)
Non-linear model
Contact with friction | $\mu = 0.4$

![Graphs showing comparison between test and model results for base shear and roof drift over time.]

- Base Shear
  - Test: 50 kN peak
  - Model: 50 kN peak
  - Difference: $-0.6\%$

- Roof Drift
  - Test: 2 mm peak
  - Model: 2 mm peak
  - Difference: $+24.7\%$

- Base Shear vs. Roof Drift
  - Test: Red
  - Model: Black
  - Difference: $+9.3\%$
Phenomenological Difference for low acceleration

With Liasons No-Separation

With Contact & Friction
Comparison

<table>
<thead>
<tr>
<th></th>
<th>Linear Model</th>
<th>Model $\mu=0.0$</th>
<th>Model $\mu=0.2$</th>
<th>Model $\mu=0.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Shear</td>
<td>+16.8%</td>
<td>+13.3%</td>
<td>-4.7%</td>
<td>-0.6%</td>
</tr>
<tr>
<td>Min Shear</td>
<td>+34.7%</td>
<td>+40.2%</td>
<td>-2.0%</td>
<td>+3.3%</td>
</tr>
<tr>
<td>Max Drift</td>
<td>+115.7%</td>
<td>+139.0%</td>
<td>+37.2%</td>
<td>+24.7%</td>
</tr>
<tr>
<td>Min Drift</td>
<td>+98.0%</td>
<td>+130.5%</td>
<td>+17.3%</td>
<td>+9.3%</td>
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</tbody>
</table>
Comparison

- **linear model**
- **model-μ=0.0**
- **model-μ=0.4**

![Graph showing base shear vs. roof drift with linear model and two non-linear models with different μ values.](image)

- 0.10M → 0.12F
- 0.45M → 0.48F
- 0.45M → 0.40F

[link to aethereng.com]
Comparison

- **Linear model**
  - $\mu = 0.0$
  - $\mu = 0.4$

Link Video: [https://www.dropbox.com/s/bvjdi3hmn5j6t1q/Cyclic_C7_High.mp4?dl=0](https://www.dropbox.com/s/bvjdi3hmn5j6t1q/Cyclic_C7_High.mp4?dl=0)
## Comparison

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</tr>
</thead>
<tbody>
<tr>
<td>$K_1$  [kN/mm]</td>
<td>86.5</td>
<td>84.0</td>
<td>116.0</td>
<td>120.0</td>
</tr>
<tr>
<td>$K_2$  [kN/mm]</td>
<td>42.9</td>
<td>39.5</td>
<td>56.4</td>
<td>59.4</td>
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<tr>
<td>$K_3$  [kN/mm]</td>
<td>15.2</td>
<td>14.1</td>
<td>20.5</td>
<td>22.0</td>
</tr>
<tr>
<td>$T_1$  model [sec]</td>
<td>0.208</td>
<td>0.214</td>
<td>0.180</td>
<td>0.176</td>
</tr>
<tr>
<td>$T_1$  test [sec]</td>
<td>0.183</td>
<td>0.183</td>
<td>0.183</td>
<td>0.183</td>
</tr>
<tr>
<td>Perc. Diff.</td>
<td>+13.7%</td>
<td>+16.9%</td>
<td><strong>-1.6%</strong></td>
<td>-3.8%</td>
</tr>
</tbody>
</table>

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Diagram:

- $K_1$: 0.10M → 0.12F
- $K_2$: 0.45M → 0.48F
- $K_3$: 0.45M → 0.40F
And for Professional Application?? 😐
1. Combined axial (compression or tension) and moment induced stresses in the longitudinal direction of the panel (grain direction of external layer);
2. Shear stresses for perpendicular-to-plane shear forces in the longitudinal direction of the panel (grain direction of external layer);
3. Combined axial (compression or tension) and moment induced stresses in the transverse direction of the panel (perpendicular-to-grain direction of external layer);
4. Shear stresses for perpendicular-to-plane shear forces in the transverse direction of the panel (perpendicular-to-grain direction of external layer);
5. In-plane shear stresses as maximum between gross, net and torsional shear.
Evolutionary Field of Verification (Transient)

20.79 sec

Link Video:
https://www.dropbox.com/s/bnwcd9tfkxqq5gl/Trans_C4-Kobe-082.mp4?dl=0

20.79 sec

Link Video:
https://www.dropbox.com/s/7y6nezyewim94d/Deformed_C4-Kobe-082.mp4?dl=0
Conclusions

- Automated Structural Modelling for designing complex structures, using contact and friction, is indeed possible, thanks to the extraordinary capabilities of code_aster.

- Results of these non-linear analyses are better than linear also for accelerations assimilable to Serviceability Limit States, given the fact that the dynamic characteristics of the structure vary also for low accelerations.

- These modelling methodologies can be extended to other structural systems (for structures where the performance or resilience is relevant).
Thank You!!