Imperial College London

RCCES Seminar Series

13th December 2017, City University of London

Seismic response of wood structures

From material damage to tall buildings

Dr Christian Málaga-Chuquitaype

Outline

- Introduction
- Damage (plasticity) model for wood
- Experimental response of timber panels
- Seismic response of timber buildings
- Concluding remarks

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- Luis Fernando Sirumbal Zapata

- Juliet Kernohan

- Cagatay Demirci

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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 CO_2 emissions)

… and we need to consider that more than half of the world's megacities are actually in earthquake prone regions

P. Jackson, **Fatal attraction:** living with earthquakes, the growth of villages into megacities, and earthquake vulnerability in the modern world. Nature (2006).

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?

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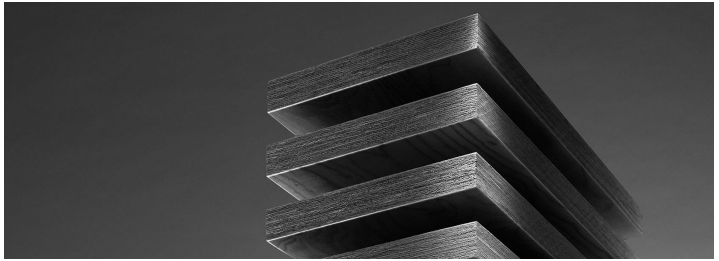
Light



Fast

Green

Photographs from Fast, Light and Green by MetzaWood

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- Coupled damage-plasticity model for wood
- Experimental response of timber panels
- Seismic response of timber buildings
- Concluding remarks

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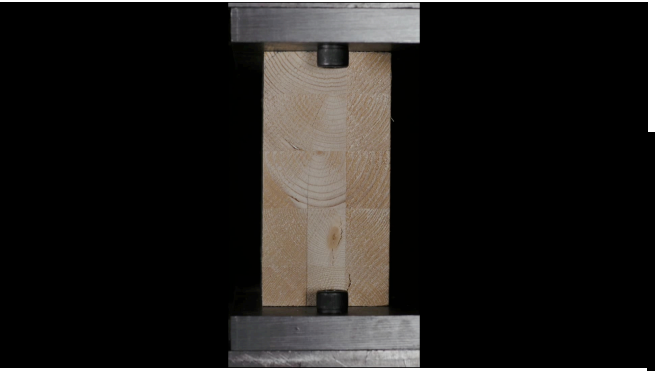
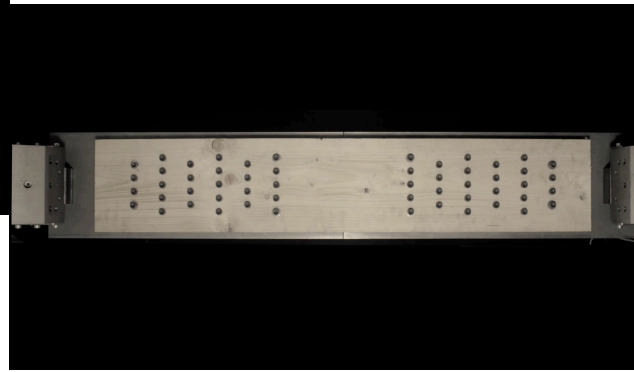


Compression perpendicular

Compression parallel



Tension

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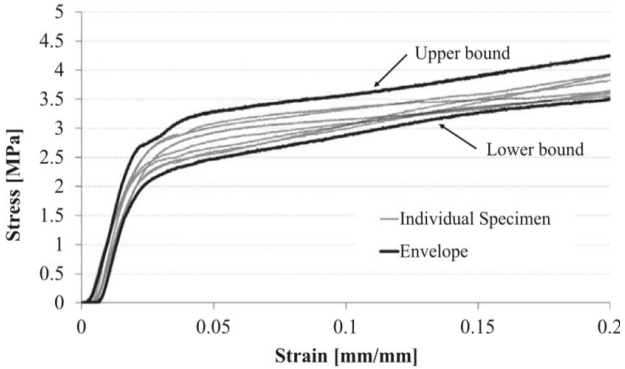

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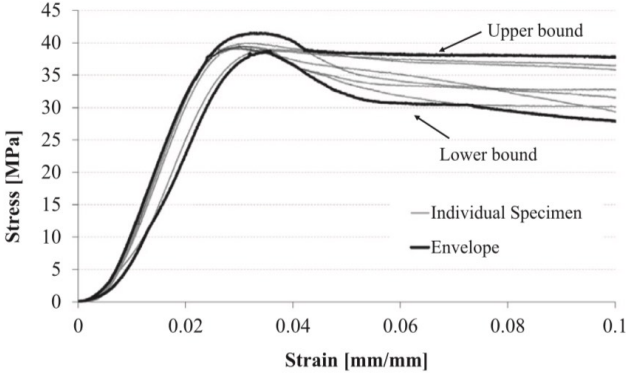
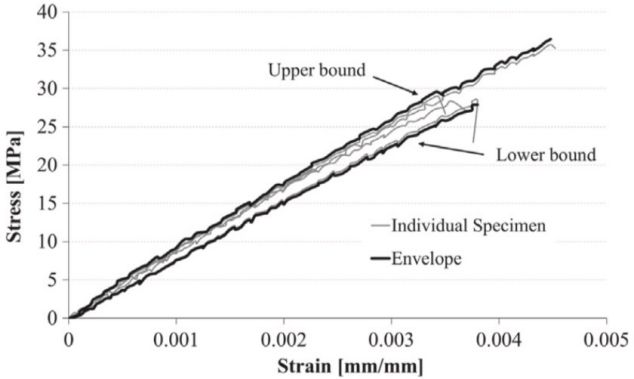


Compression parallel



Tension

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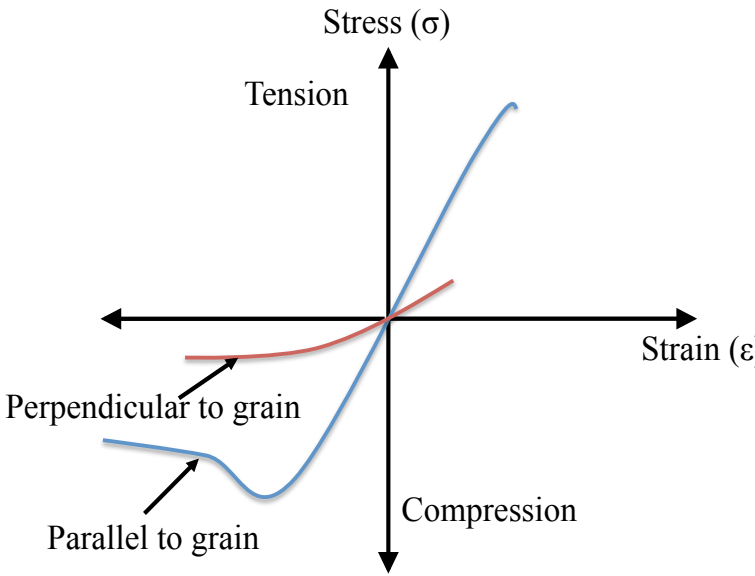
- The performance of timber structures is governed by the nonlinear response in the connection zones (high deformation levels and stress concentrations)
- These zones are also susceptible to significant load-reversals during the service life of structures, especially during extreme load scenarios such as earthquakes



Schematic stress-strain relationship for wood

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

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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

$$\boldsymbol{\sigma} = \boldsymbol{M}(\boldsymbol{D}) : \bar{\boldsymbol{\sigma}}$$

Anisotropic damage is considered by assigning different values to the damage variable components of D (2nd or 4th order tensor)

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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**.

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Spectral decomposition of the effective stress tensor

$$\bar{\boldsymbol{\sigma}}^{+} = \sum_{i=1}^{3} \langle \bar{\sigma}_i \rangle \boldsymbol{p}_i \otimes \boldsymbol{p}_i$$

$$\bar{\boldsymbol{\sigma}}^{-} = \bar{\boldsymbol{\sigma}} - \bar{\boldsymbol{\sigma}}^{+}$$

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

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Isotropic damage

$$\boldsymbol{\sigma} = (1-\omega^{+})\bar{\boldsymbol{\sigma}}^{+} + (1-\omega^{-})\bar{\boldsymbol{\sigma}}^{-}$$

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

$$f_d^{\pm}(\bar{\boldsymbol{\sigma}}^{\pm}, r^{\pm}) = \bar{\tau}^{\pm} - r^{\pm}$$

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

$$\bar{\tau}^{\pm} = \sqrt{\frac{1}{2}\bar{\boldsymbol{\sigma}}^{\pm T}\boldsymbol{H}^{\pm}\bar{\boldsymbol{\sigma}}^{\pm}}$$

$$(f_X^{\pm}, f_Y^{\pm}, f_Z^{\pm}, f_{XY}, f_{YZ}, f_{ZX})$$

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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)

- The **Damage Evolution Law** defines the variation of the damage variable as a function of the threshold variable

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Damage evolution law - tension

$$\omega^{\pm} = g_d^{\pm}(r^{\pm})$$

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

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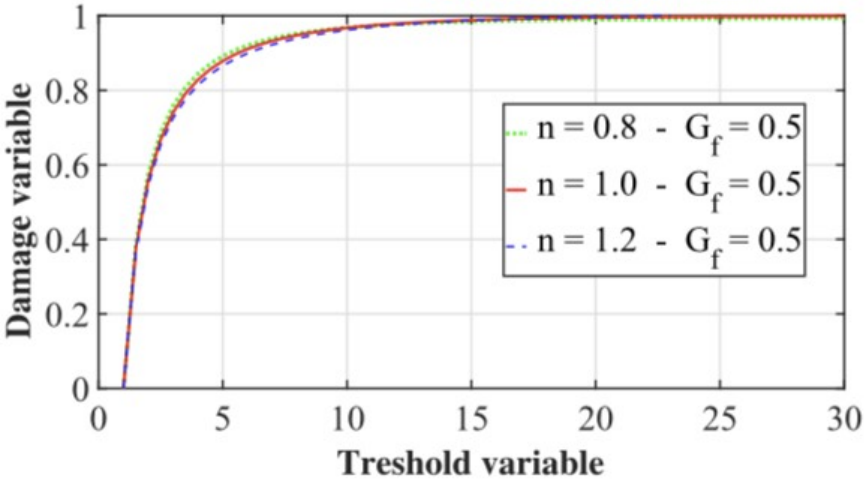

(b) Damage variable, ω^{+}.

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Damage evolution law - tension

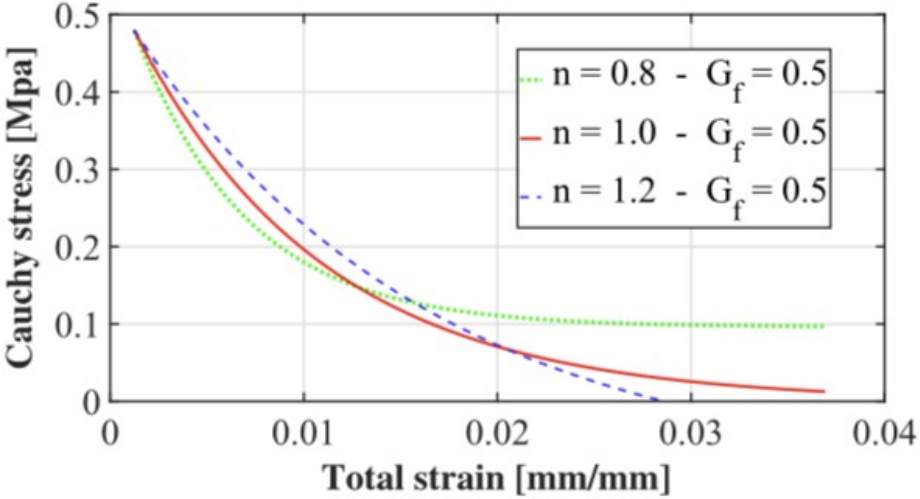
$$\omega^{\pm} = g_d^{\pm}(r^{\pm})$$

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

Calibration parameter

Constant dependent on the mesh size (through the characteristic length)

$$\sigma^{+} = \frac{r^{+}}{r_0} f_{max}[1 - g_d{}^{+}(r^{+})]$$



(a) Cauchy stress, σ^{+}.

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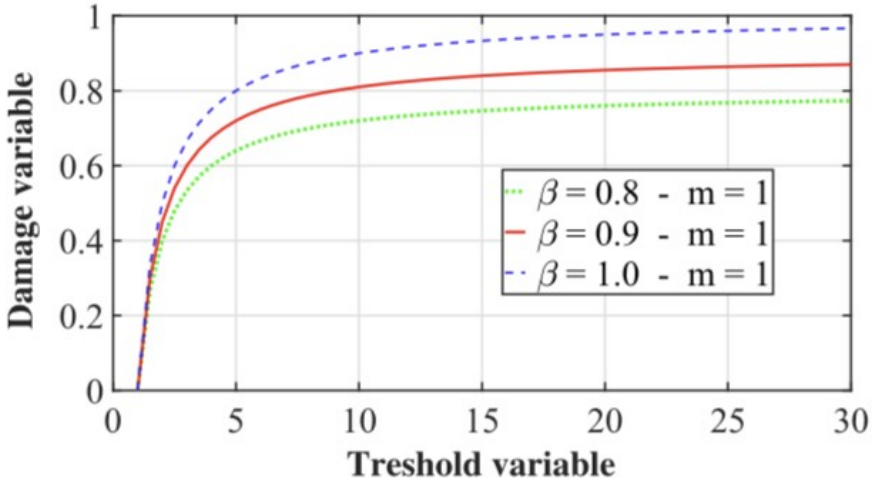
Damage evolution law - compression

$$\omega^{\pm} = g_d^{\pm}(r^{\pm})$$

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

Calibration parameter



(b) Damage variable, ω^{-}.

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Damage model

- Damage criteria function

$$f_d^{\pm}(\bar{\boldsymbol{\sigma}}^{\pm}, r^{\pm}) = \bar{\tau}^{\pm} - r^{\pm}$$

- Damage evolution law

$$\omega^{\pm} = g_d^{\pm}(r^{\pm})$$

- Loading-unloading conditions

$$f_d^{\pm} \leqslant 0; \quad \dot{r}^{\pm} \geqslant 0; \quad \dot{r}^{\pm} f_d^{\pm} = 0$$

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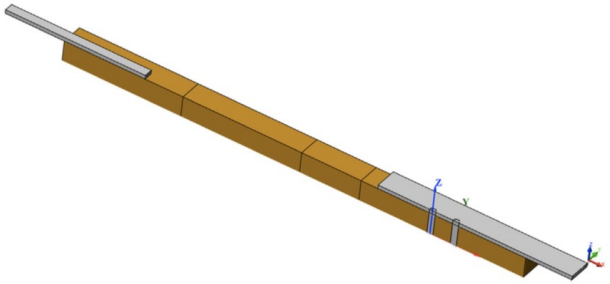
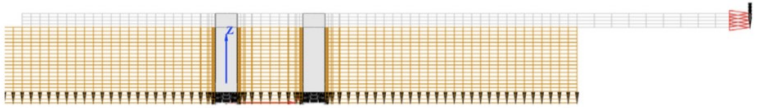
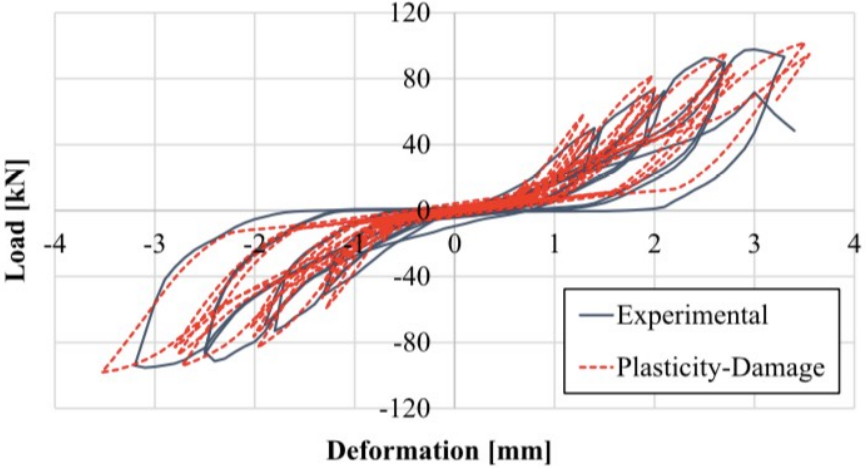
Model verification

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



(a) 3D view





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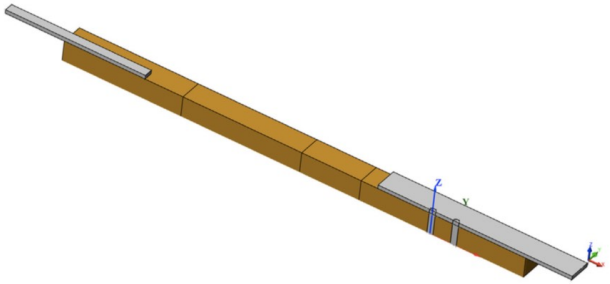

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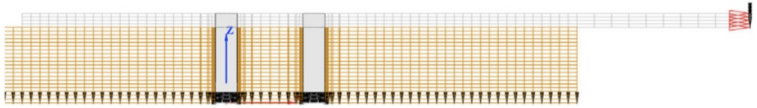

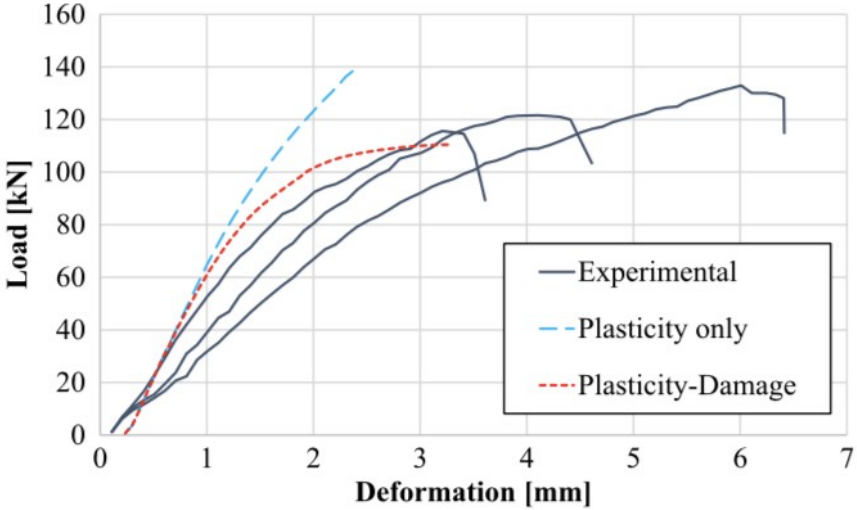

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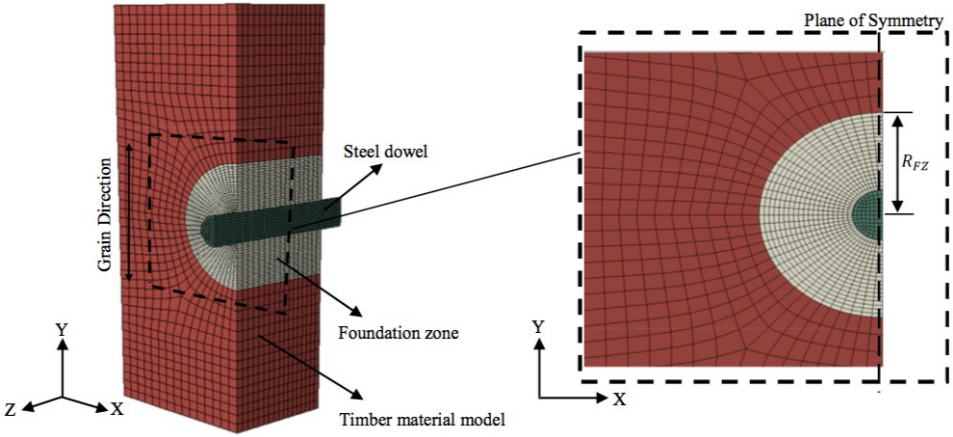
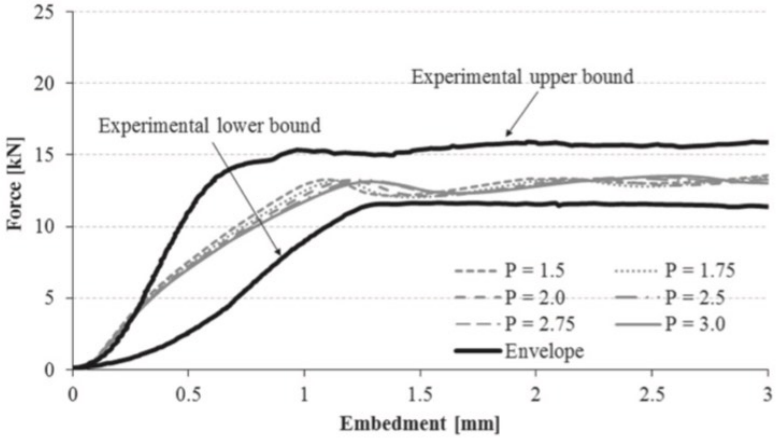
Other ways of modelling damage

- Foundation modelling approach – embedment tests PARALLEL





a) Parallel to grain

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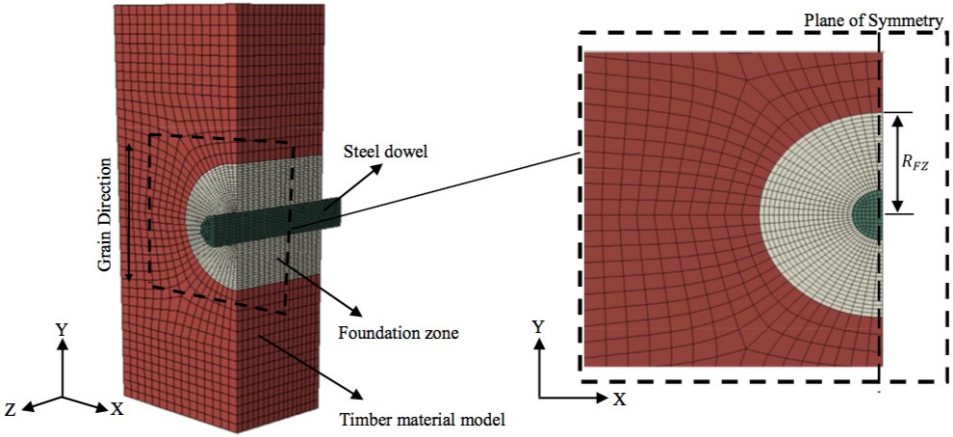
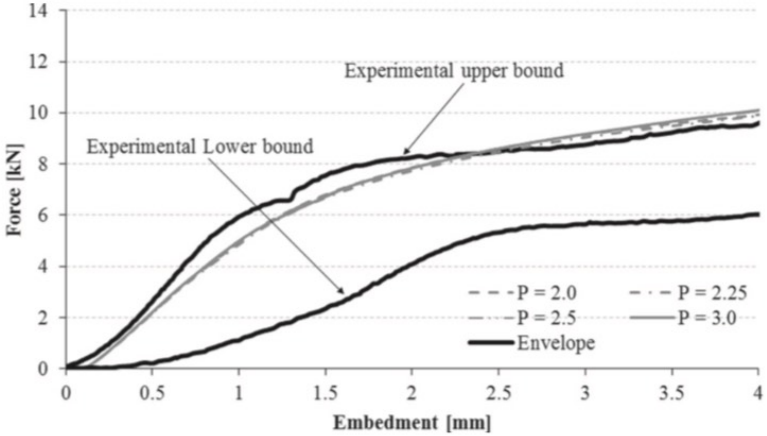
Other ways of modelling damage

- Foundation modelling approach – embedment tests PERPENDICULAR





b) Perpendicular to grain

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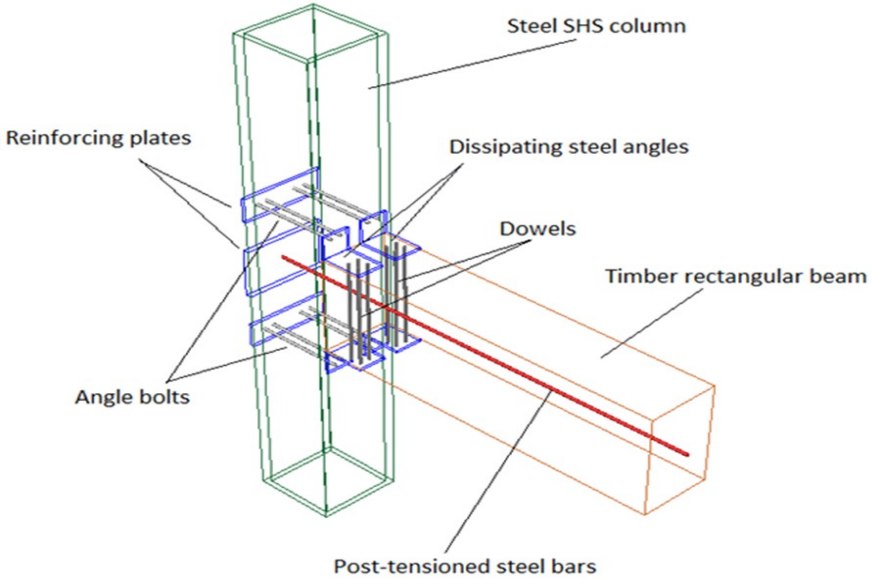
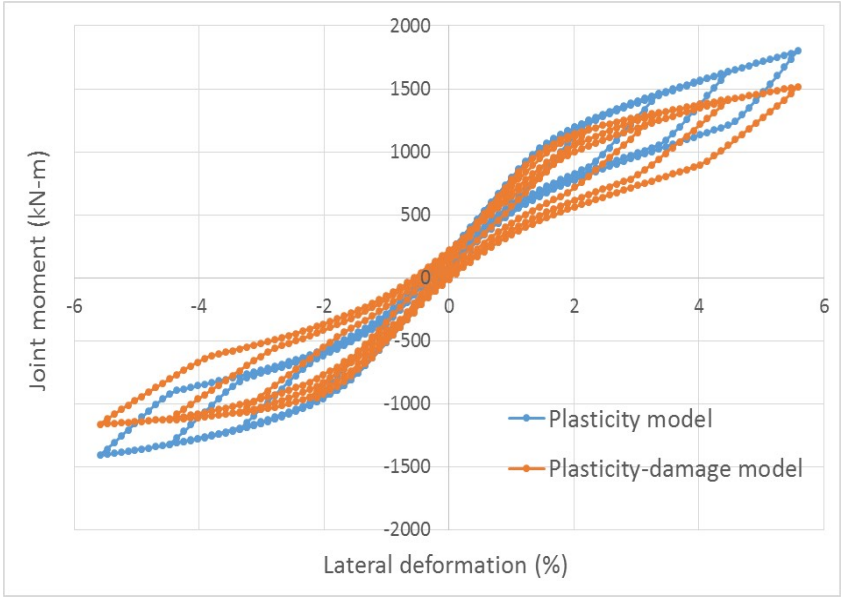
Cyclic response of post-tensioned timber frames





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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

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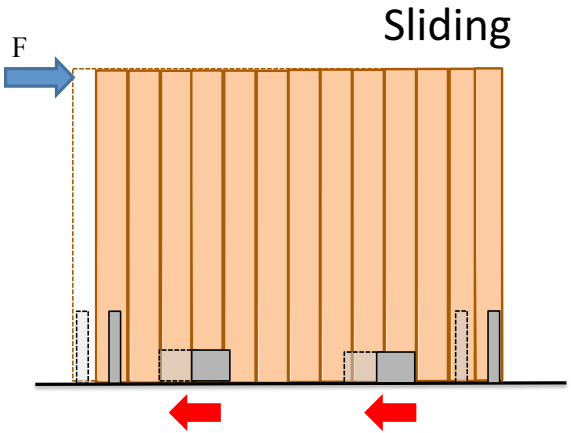
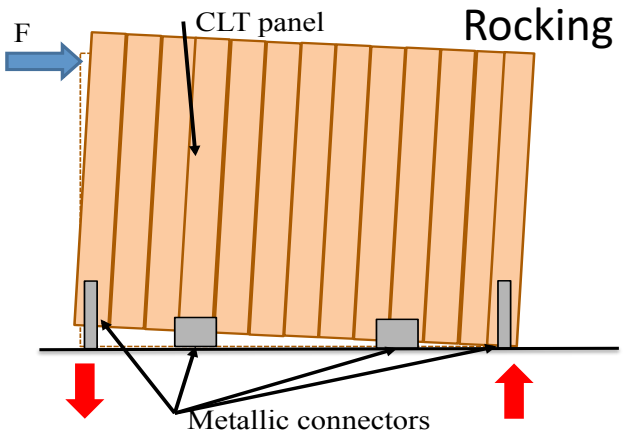
Lateral deformation modes of timber CLT walls

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





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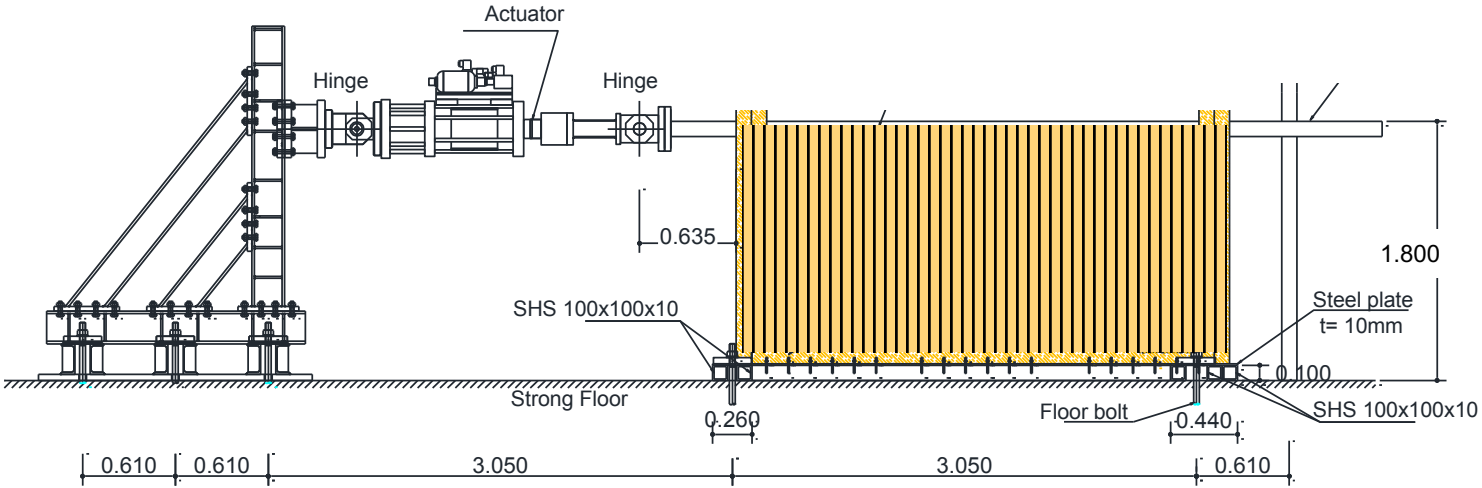
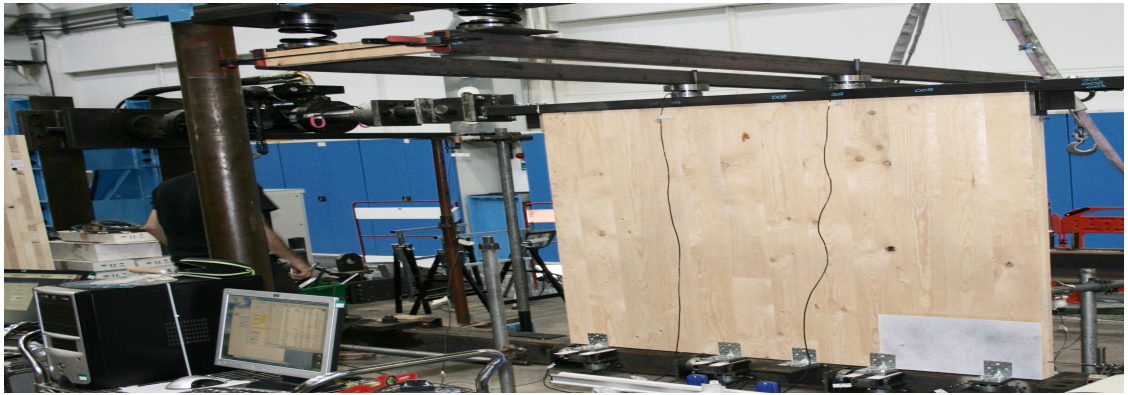


The Institution of Structural Engineers

RAMBOLL

rothoblaas

B&K STRUCTURES
OPTIMISED HYBRID SOLUTIONS



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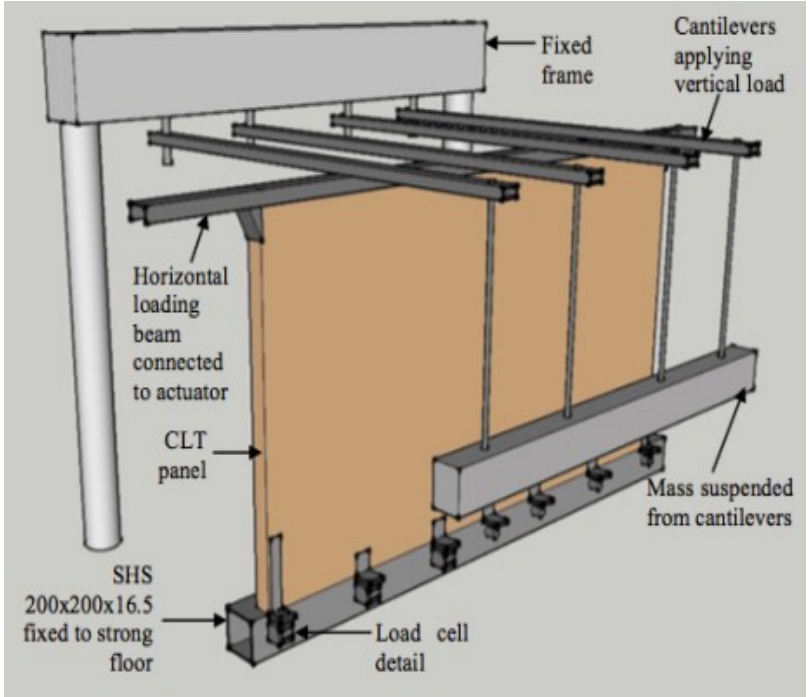

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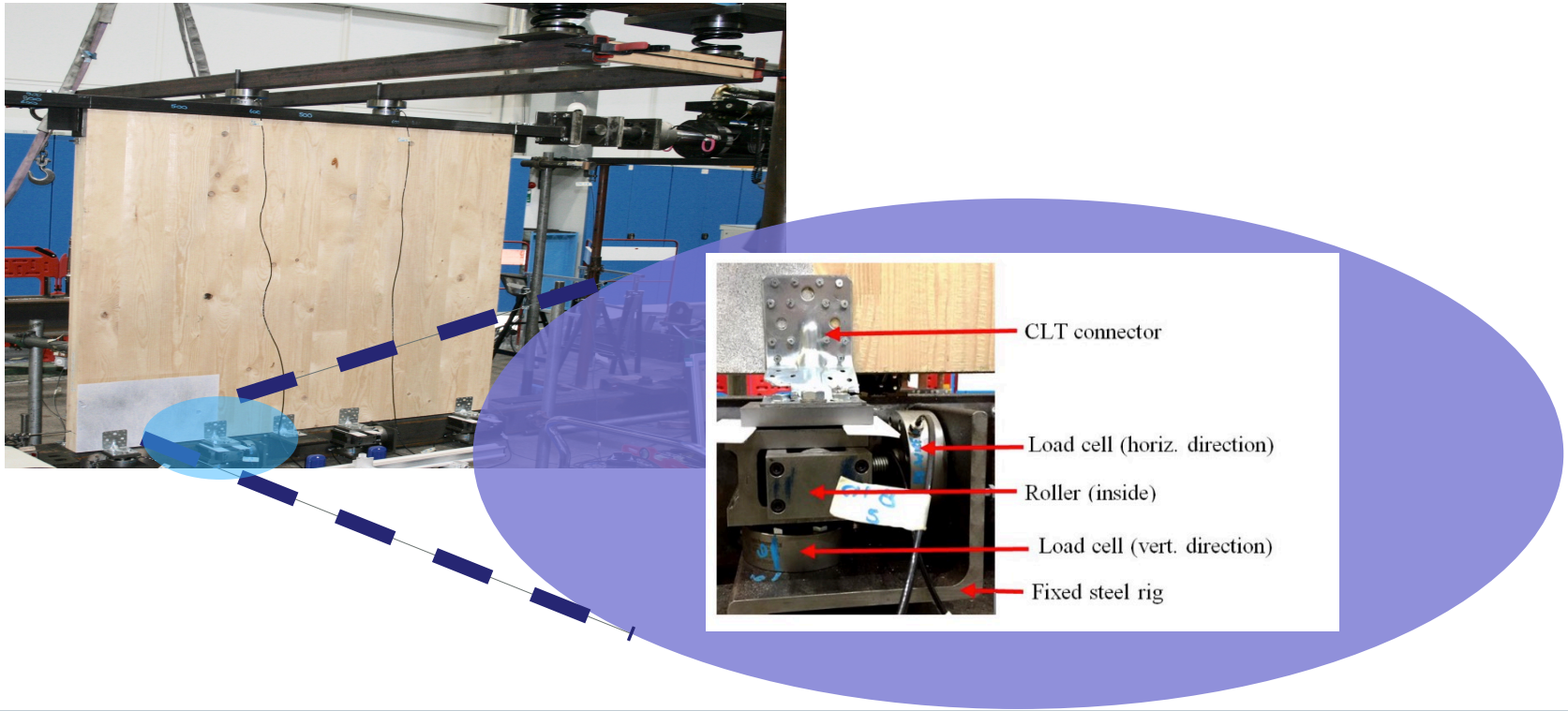

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Summary of tests

Specimen	P1	P2	P3	P4	P5	P6
Dimensions H x L [m]	1.8x1.8	1.8x1.8	1.8x2.5	1.8x2.5	1.8x3.2	1.8x3.2
Bracket configuration	5 x WB100 brackets	5 x WB100 brackets	5 x WB100 brackets	3 x WB100 brackets + 2 WHT340 hold-downs	6 x WB100 brackets	4 x WB100 brackets + 2 WHT340 hold-downs
Vertical load [kN/m]	3.3	12	15	15	13	13

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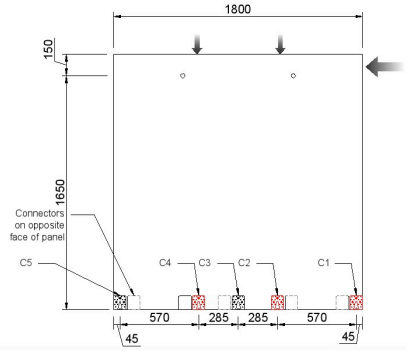

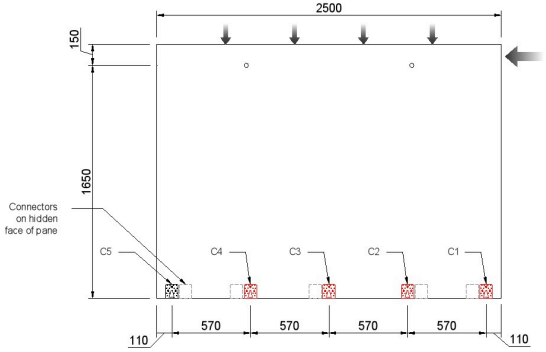

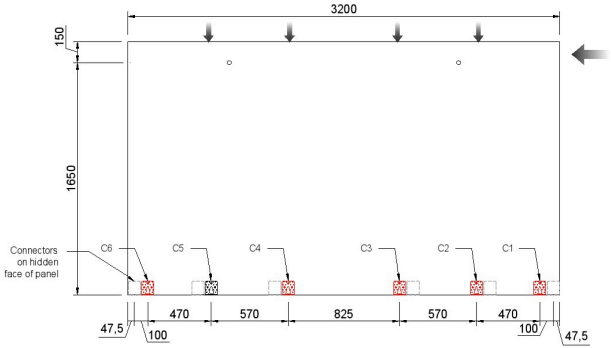

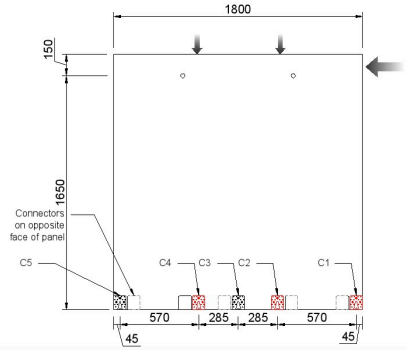

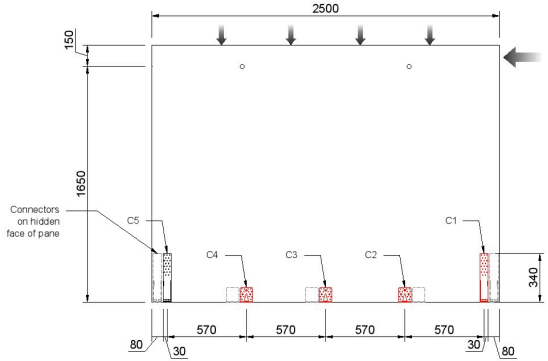

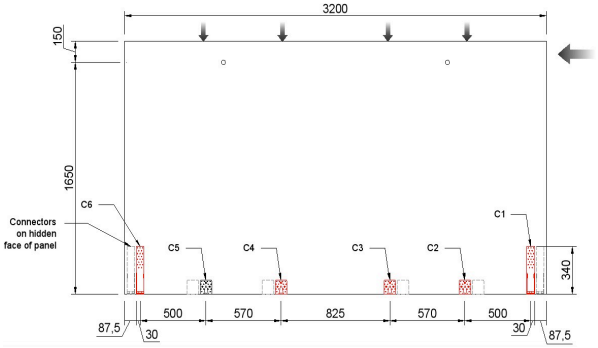

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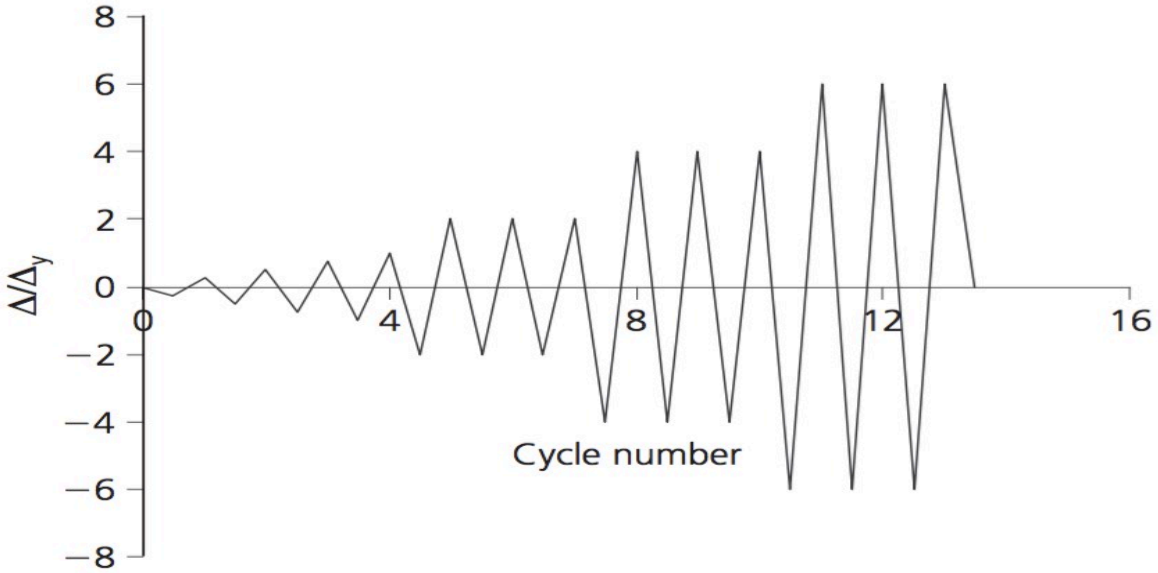
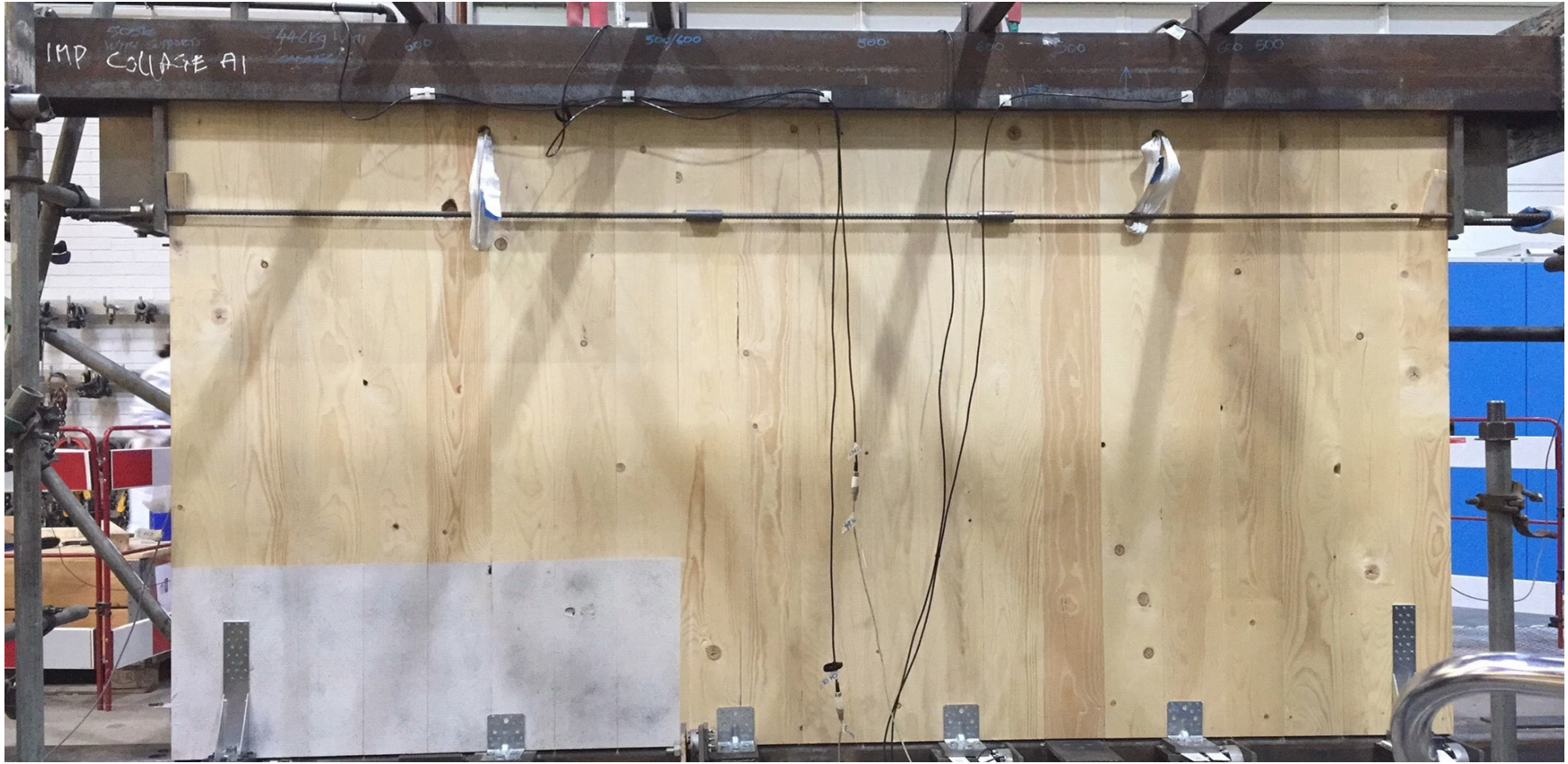
Cyclic protocol (EN 12512)

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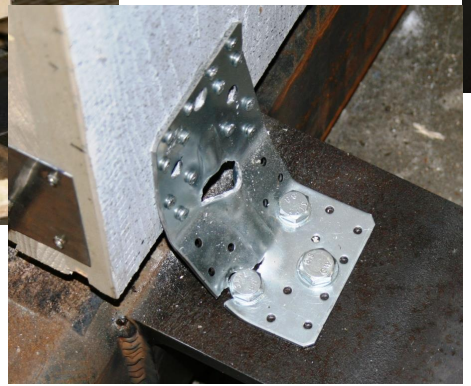
Failure modes



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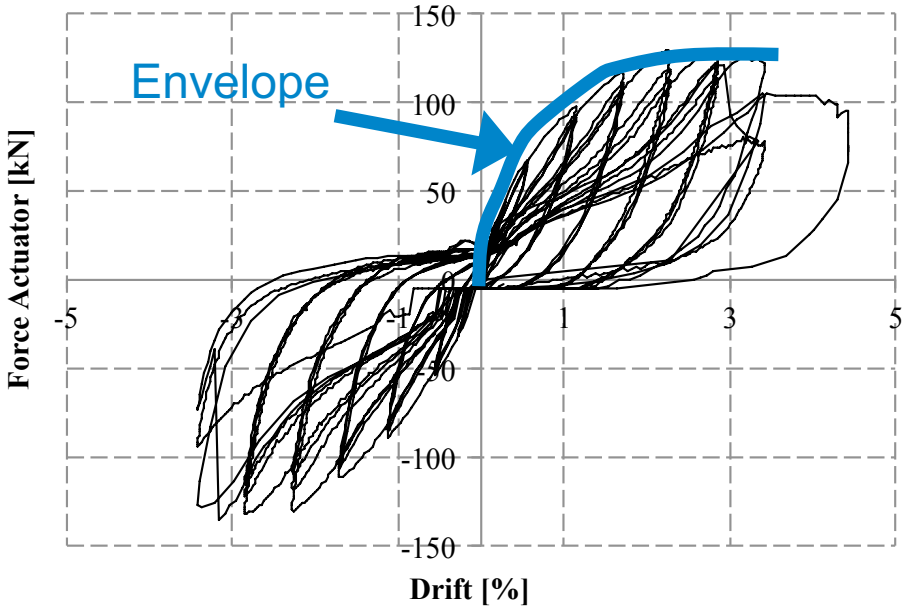
Hysteretic response – Specimen P3 (all SB, 2.5 m)



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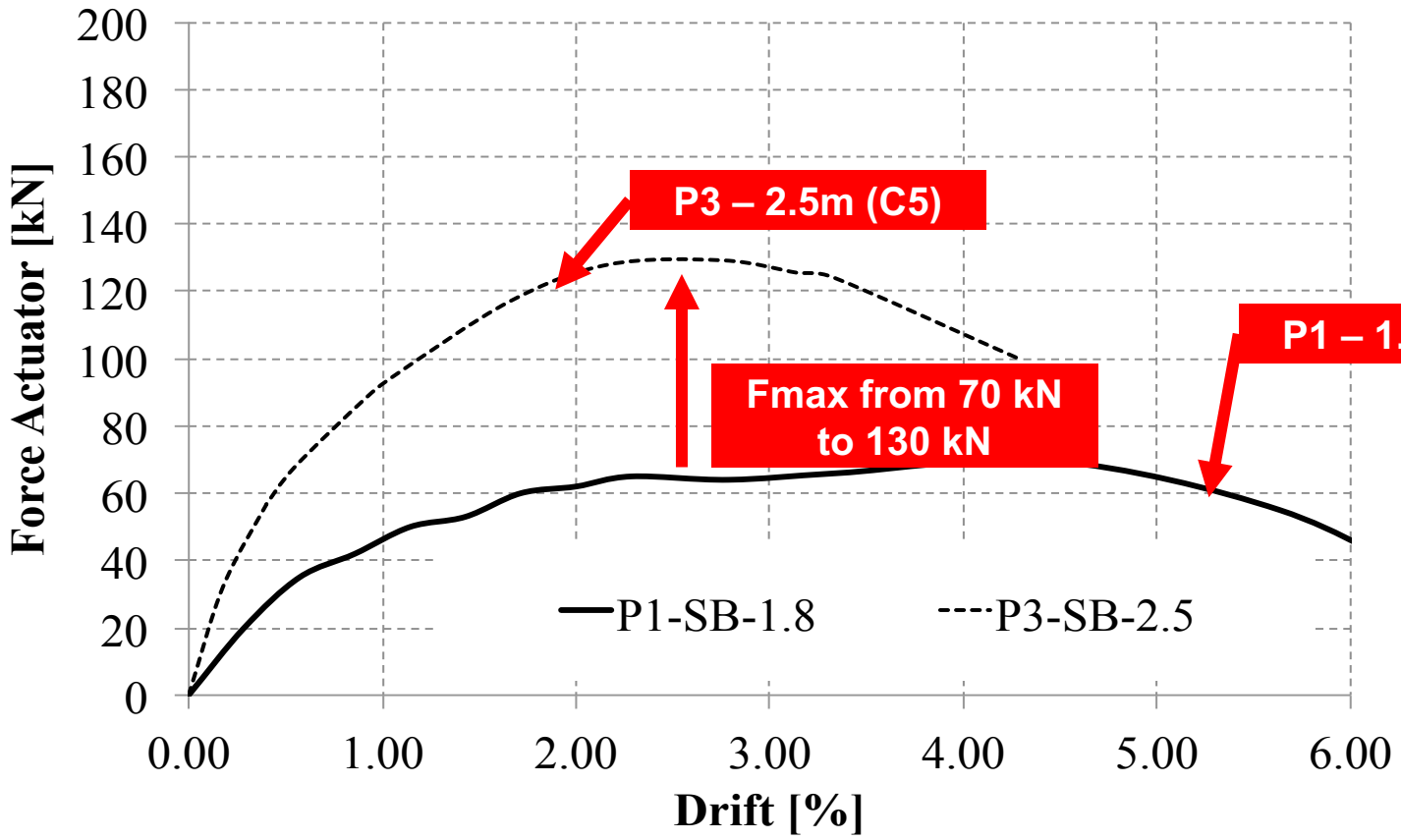
Effects of length of panel



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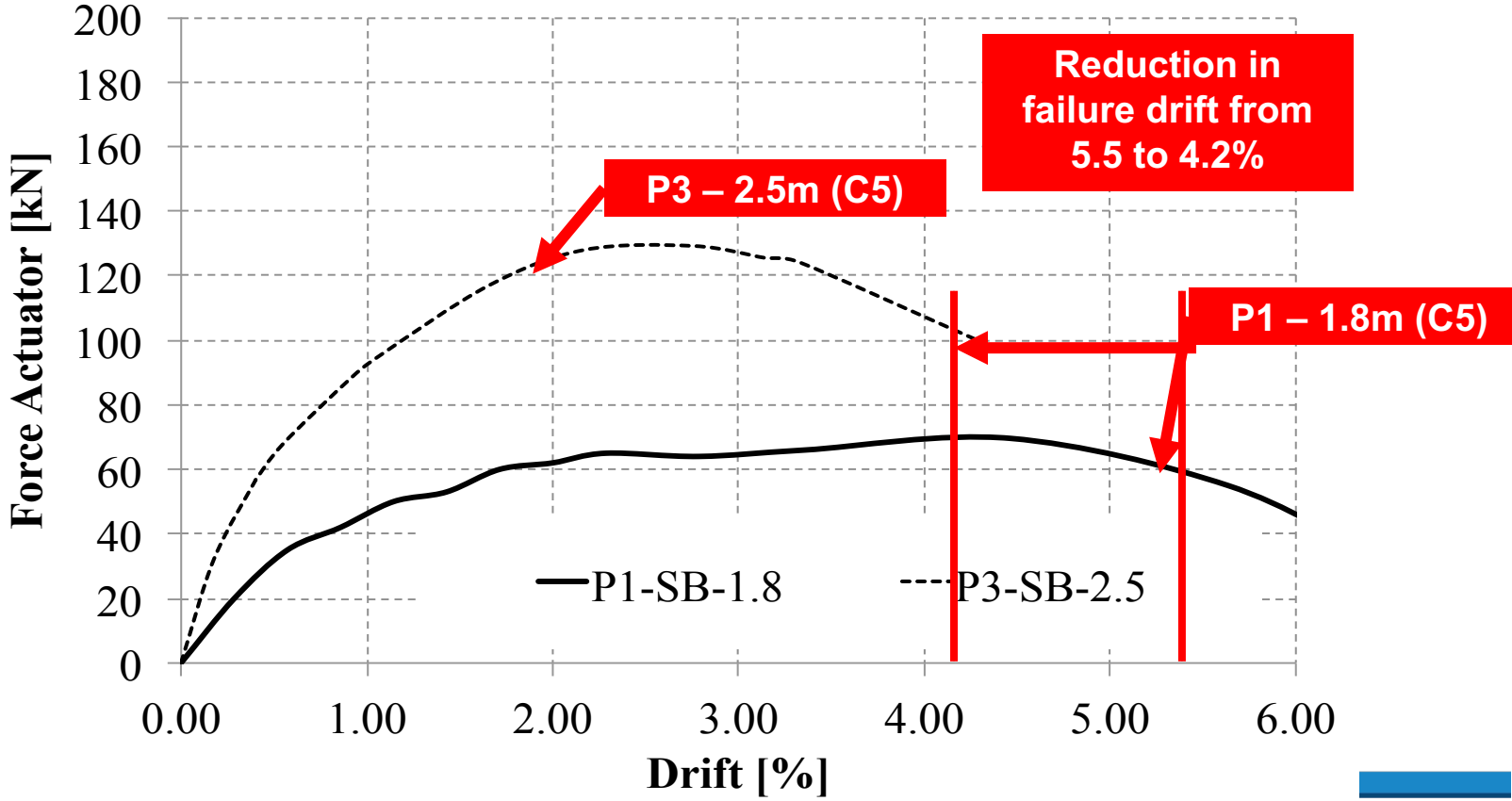

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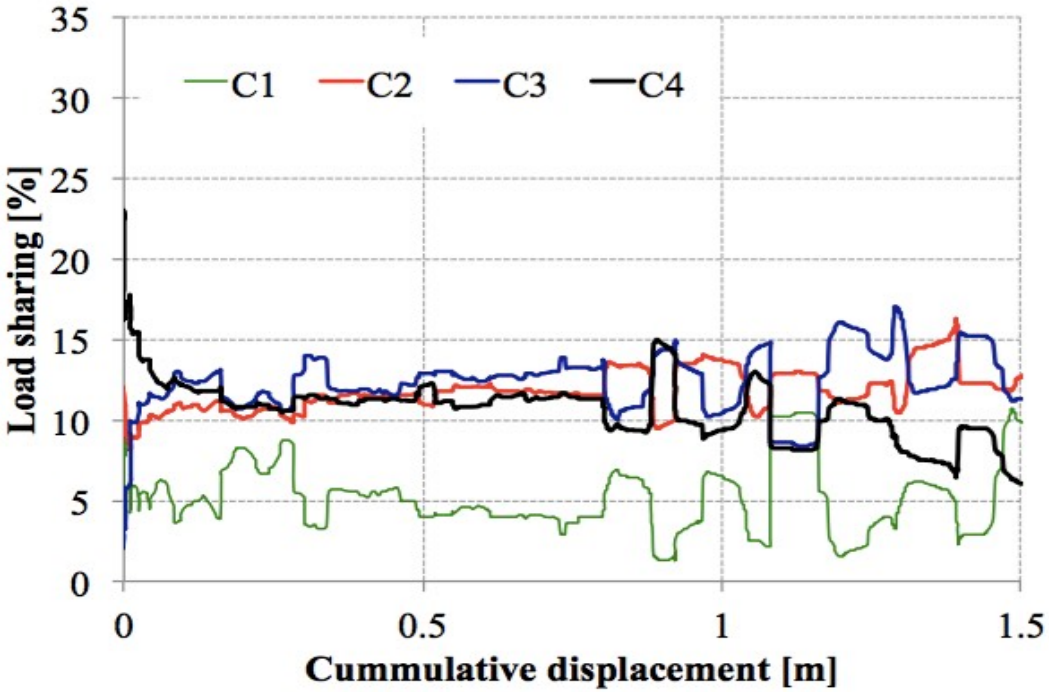
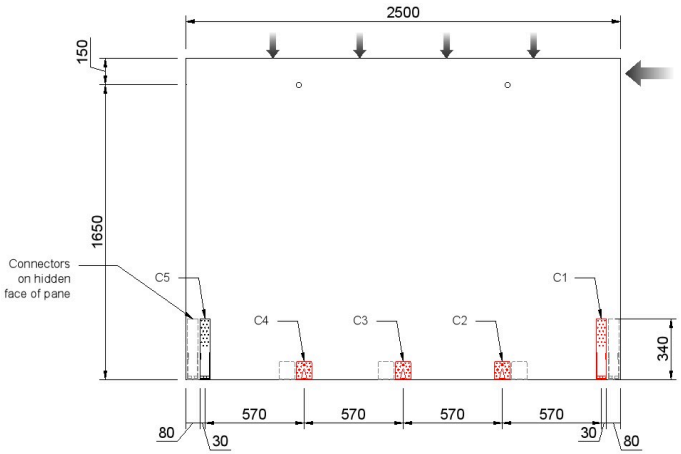
Evolution of shear forces in P4





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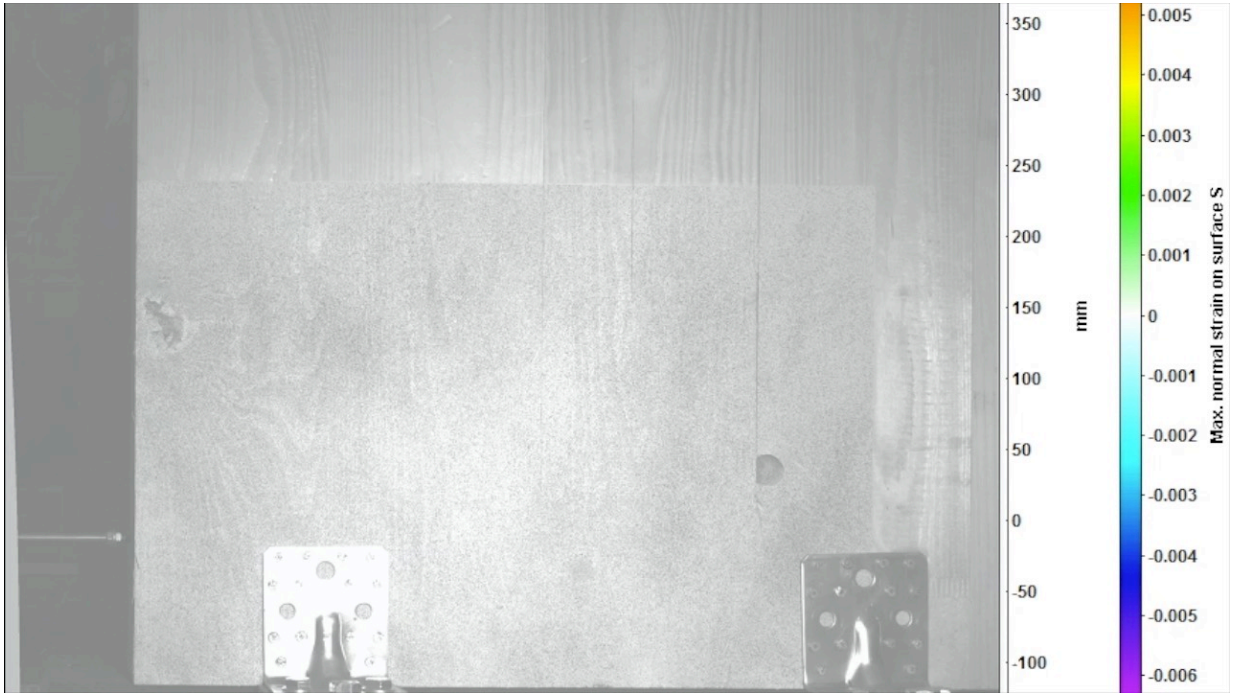
Maximum normal strain field in P1-SB



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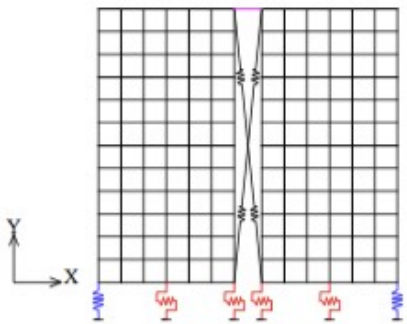
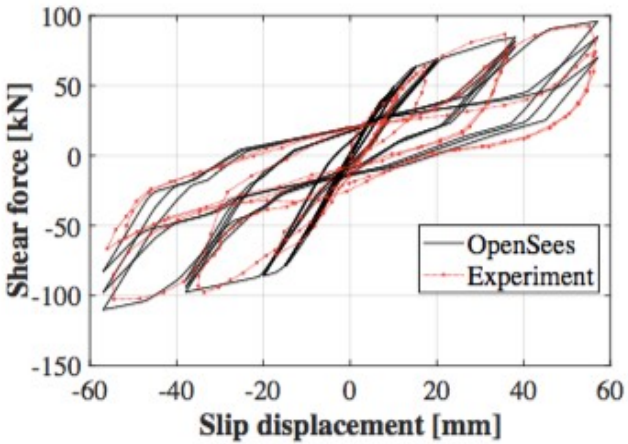
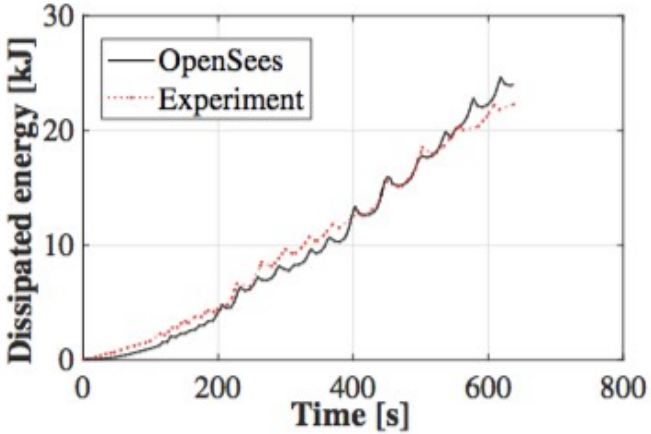
Cyclic response of CLT walls and cores



OpenSees model



Experimental and numerical hysteresis



Experimental and numerical cumulative energy

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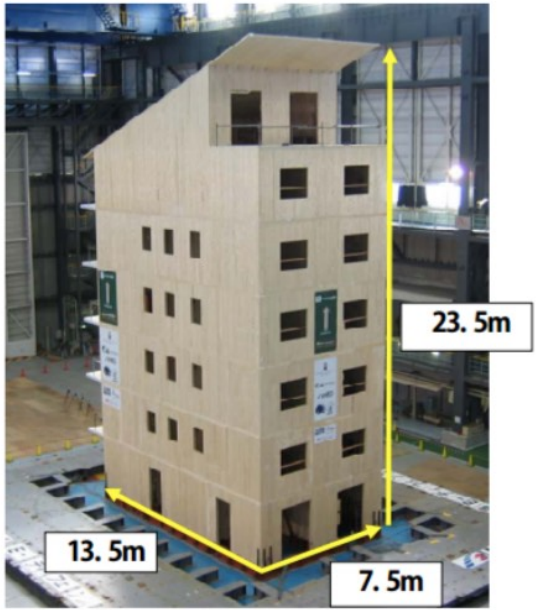
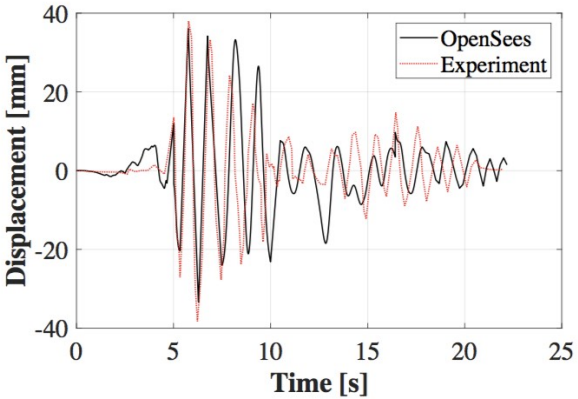
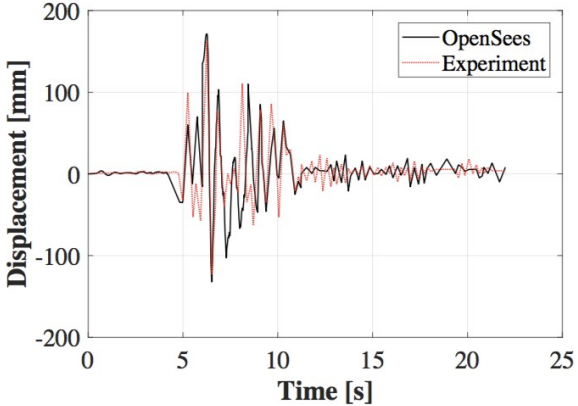
Dynamic response of CLT buildings





Displacement history at 1st level



Displacement history at 7th level

Experiments by Ceccotti et al. (2006; 2013)

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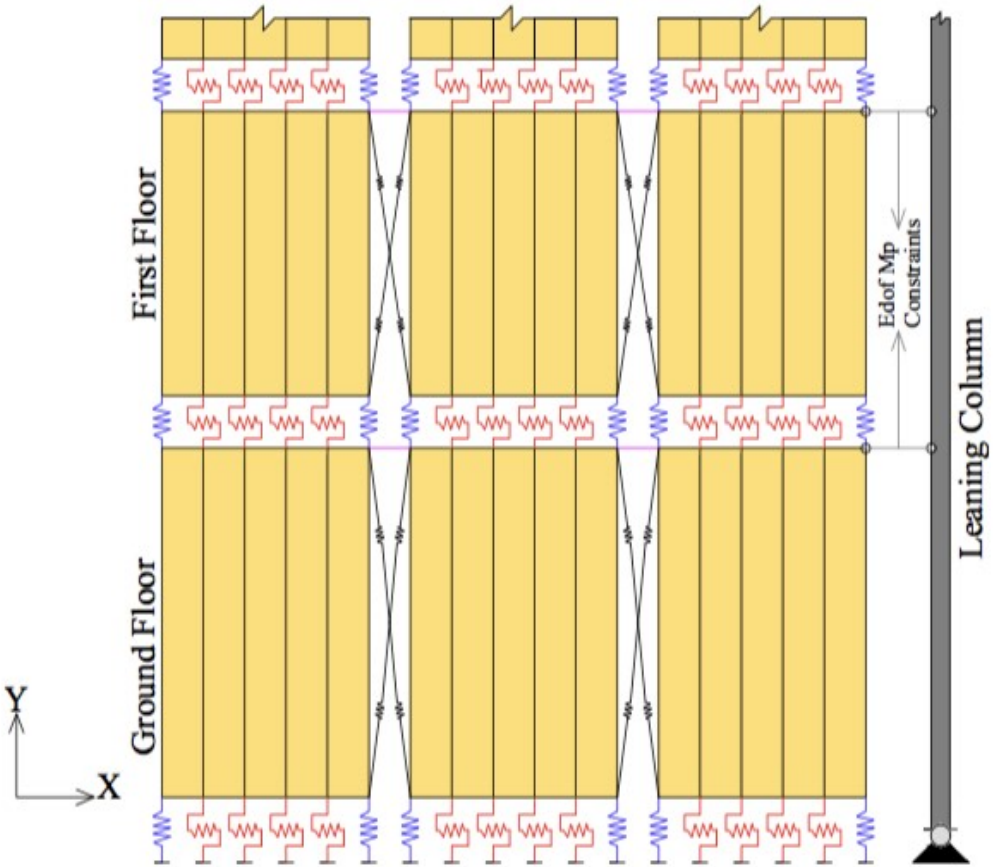
Building database

- 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)



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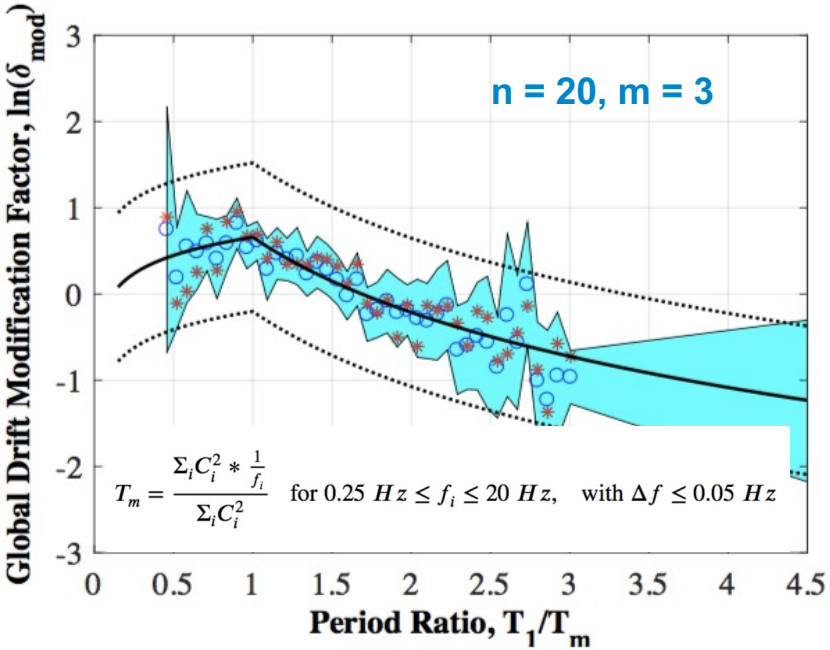
Assessment of seismic drift demands

- 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



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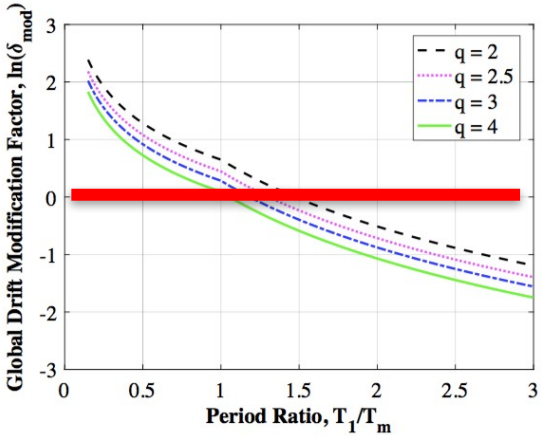
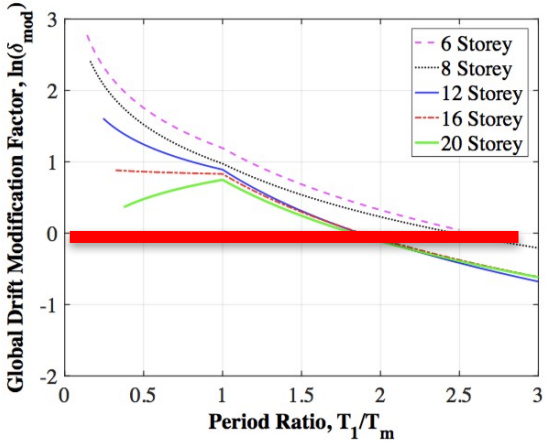
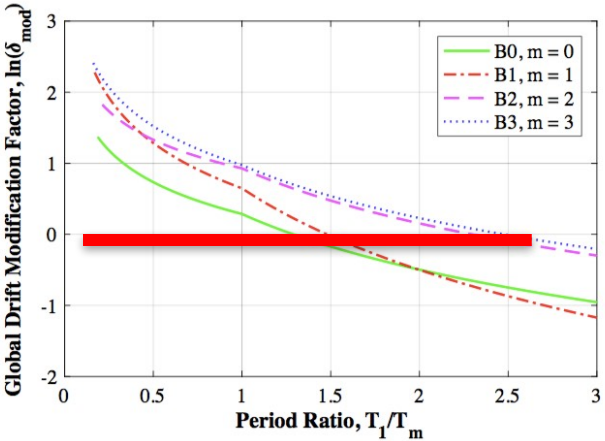


Influence of behaviour factor
(8 storey building, m=1)



Influence of number of storeys
(q =3)



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

Outline

- Introduction
- Damage (plasticity) model for wood
- Experimental response of timber panels
- Seismic response of timber buildings
- Concluding remarks

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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 conduced experiments are fundamental in developing our understanding of the mechanical response of (wood) structures ultimately leading to greater societal and economic benefits and impact

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- http://www.imperial.ac.uk/emerging-structural-technologies

Thank you!

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Emerging Structural Technologies and Design