ROBUSTNESS OF MULTI-STORY TIMBER BUILDINGS IN SEISMIC REGIONS

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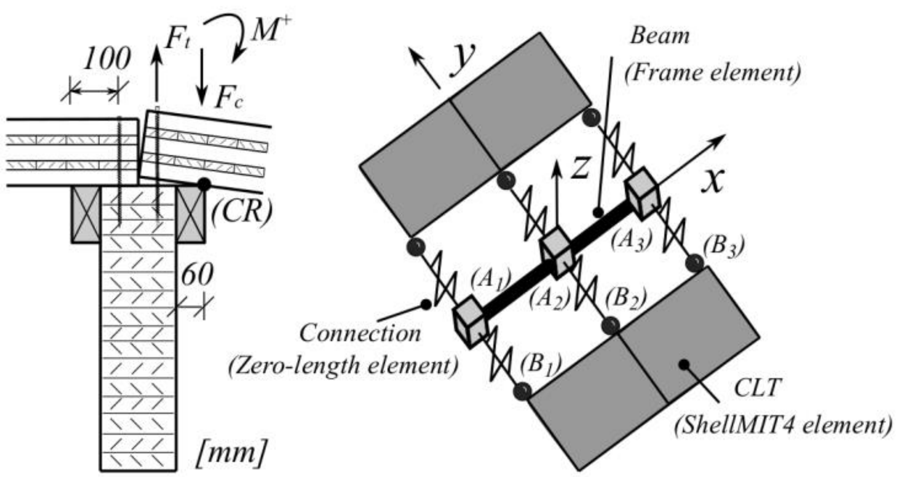


1. Outline

- Introduction and motivation
- Thesis outline
- Shake-table test and modelling of CLT diaphragms
- Seismic assessment of heavy-timber structures
- Robustness assessment of heavy-timber structures
- Conclusions and Future developments

2. Introduction and motivation

- Glued Laminated Timber (GLT) and Cross-Laminated Timber (CLT)
  - Enable construction efficiency
  - Reduced environmental impacts
  - **Low weight-to-strength ratio**

Suitable for locations where high intensity ground motions are likely to occur

Arbora complex in Montreal (Oberholzer, 2016)

Redbridge School in Lisbon

2. Introduction and motivation

Seismic design provisions

- Simplicity, Uniformity and Symmetry
- **Redundancy**
- Bi-directional strength and stiffness
- Torsional resistance and stiffness
- Adequate force **transfers through diaphragms** at storey level
- Adequate foundations

Robustness design recommendations

- **Alternate load paths**
- Effective horizontal ties
- Vertical ties to ensure stability
- Effective anchorage of suspended floor to walls
- **Ductility**
- **Redundancy**

The **failure of timber** elements **is usually brittle**, whereas **the failure of connections** between timber elements **can be ductile**. Being constructed in seismic areas, the requirements promoted by the **design codes are objectively more strict regarding connections** and the sizes of timber members.

3. Thesis Outline

Chapter 2

Shake-table test and modelling of CLT diaphragms

- Evaluate diaphragm design forces
- Numerical model strategy for design

Chapter 3

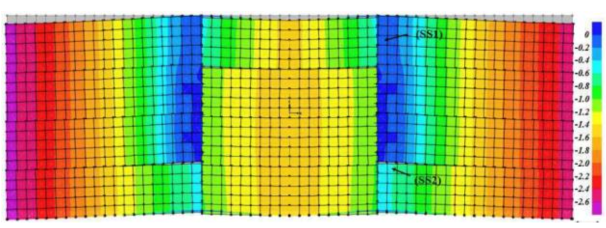
Seismic assessment of heavy-timber structures

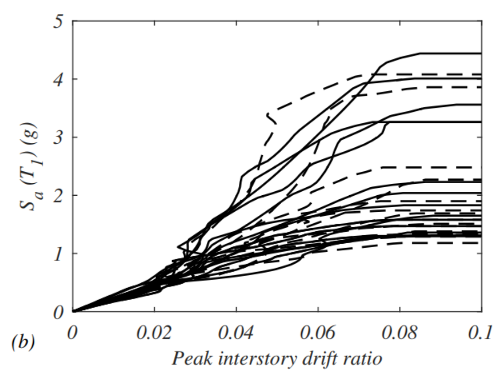
- Pushover and IDA analysis
- Probabilistic assessment
- Fragility Curves

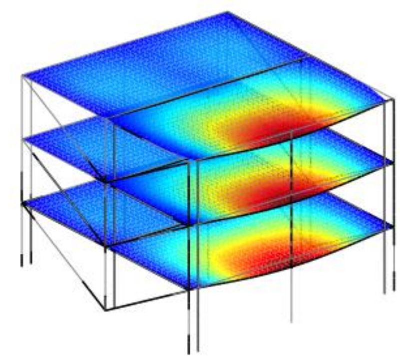
Chapter 4

Robustness assessment of heavy-timber structures

- Distinct initial damage scenarios
- Alternative Load Path Analysis
- Fragility Curves







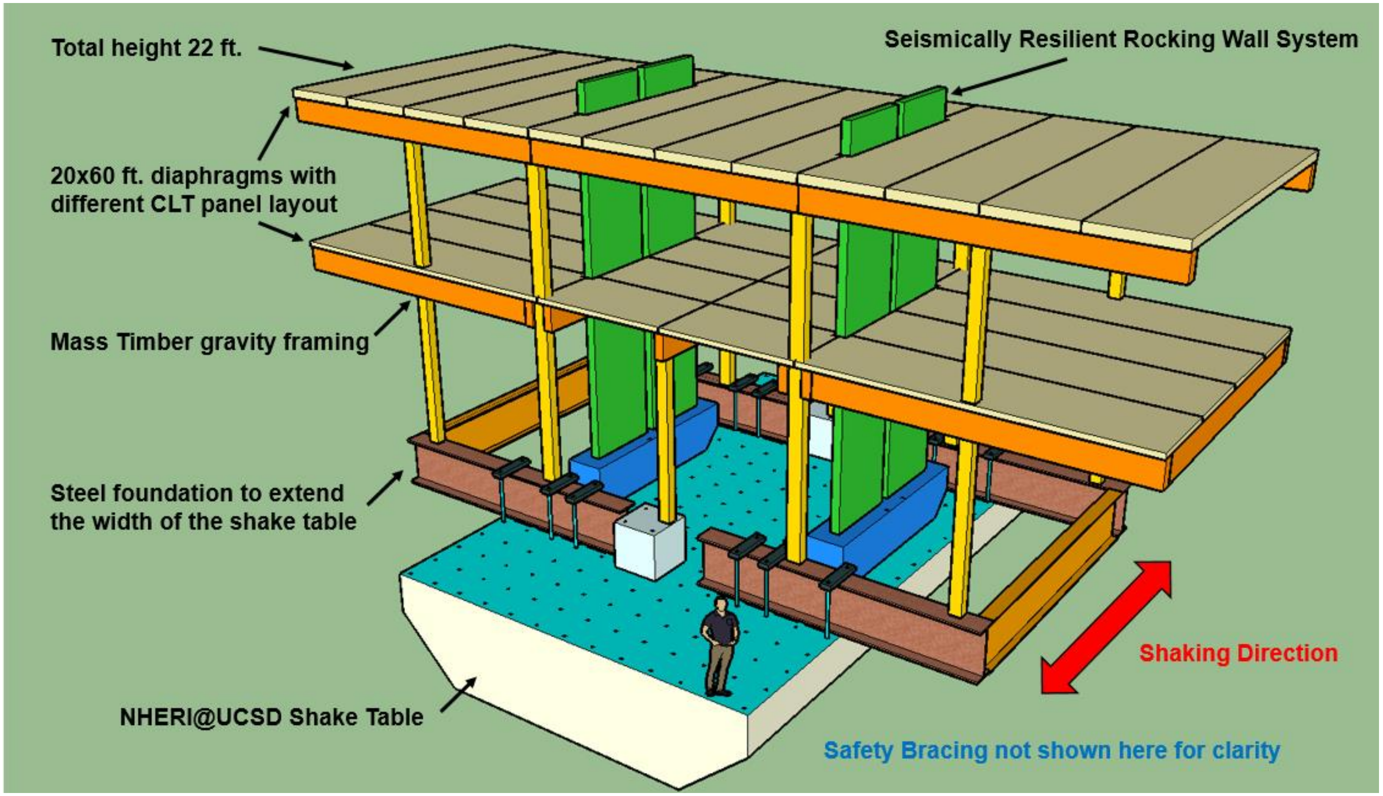
4. Shake-table test and modelling of CLT diaphragms

- Objectives
  - Improve the understanding of the behavior of CLT diaphragms and develop a **computational modeling approach** that provides validated results **using experimental data collected during the shake-table testing** of a two-story mass-timber prototype building.

4. Shake-table test and modelling of CLT diaphragms

- Experimental Setup
  - Three Wall Systems Tested
  - Designed for locations Washington, Berkeley, and San Francisco

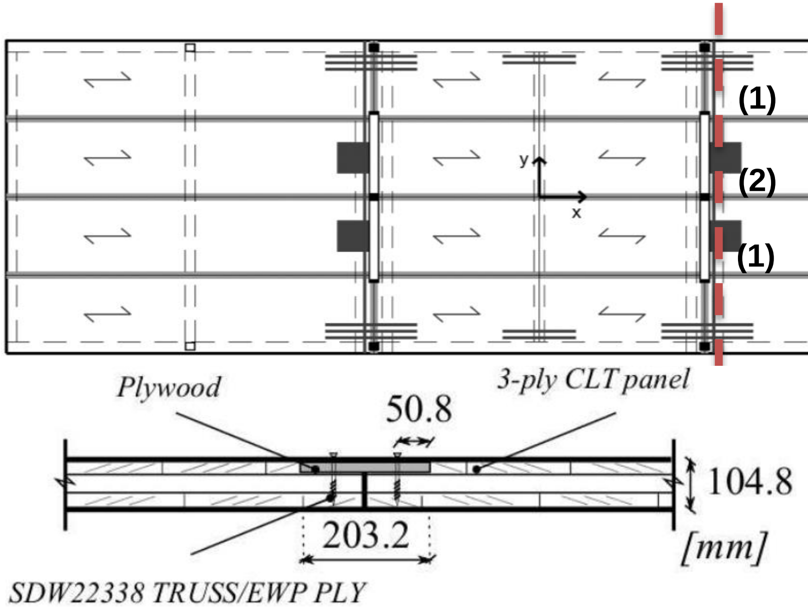
Two types of diaphragms:
- CLT only
- CLT/concrete

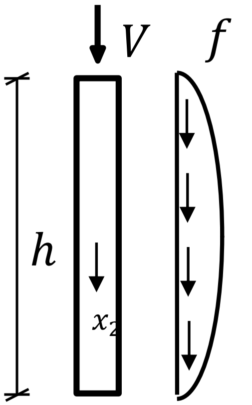


4. Shake-table test and modelling of CLT diaphragms

Surface splines

- Design
  - **Alternative Diaphragm Seismic Design Force Level** of ASCE 7-16
  - CLT diaphragms were designed in accordance **with principles of mechanics** with values of **fastener and member strength according to latest test results** and NDS.





Design force :

$$V = A \cdot C_{pf} \cdot w_{pf}$$

Shear flow calculation :

$$f = \frac{V}{h}\left[\frac{3}{2} - 6\left(\frac{x_2}{h}\right)^2\right]$$

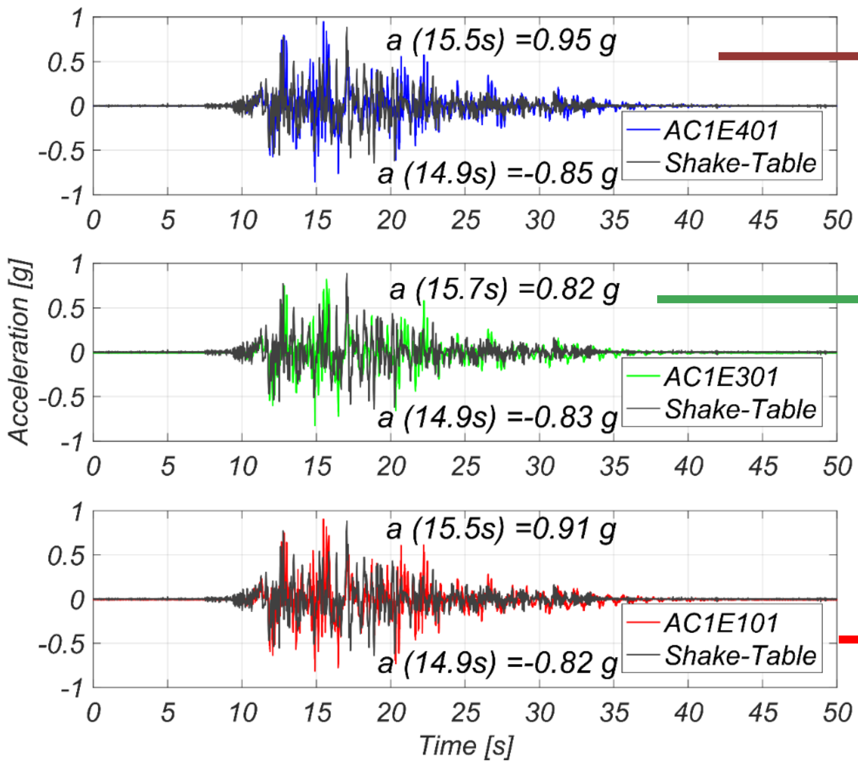
C_{pf} - Diaphragm design acceleration coefficient at the floor

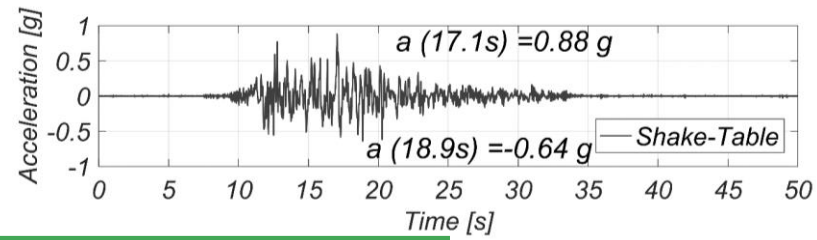
w_{pf} - weight tributary to the floor

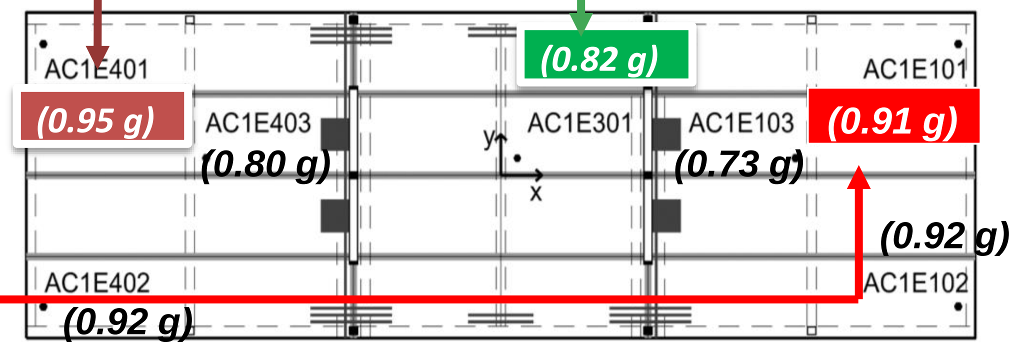
4. Shake-table test and modelling of CLT diaphragms

- Experimental results
  - Average accelerations at diaphragm levels

Northridge (MCE) – Scale Factor 1.2







Higher accelerations at the cantilevered ends

4. Shake-table test and modelling of CLT diaphragms

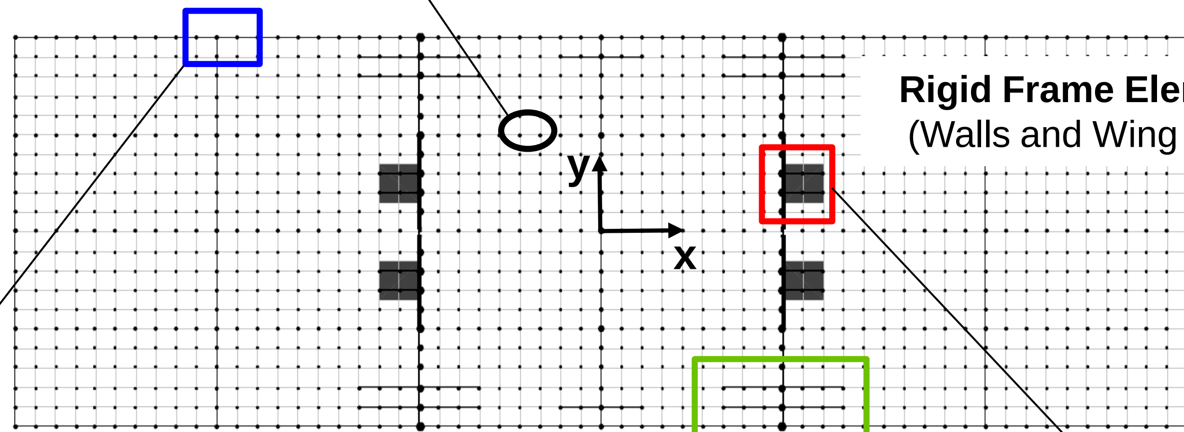
Orthotropic Four-Node Shell Elements
(CLT panels)

Rigid Zero-length elements
(Wall to Diaphragm Connections)

Rigid Zero-length elements
(Beam-to-Beam Connections)

Rigid Frame Elements
(Walls and Wing plates)

Zero-length elements
(Nonlinear Behavior)
(CLT-to-Beam Connections)

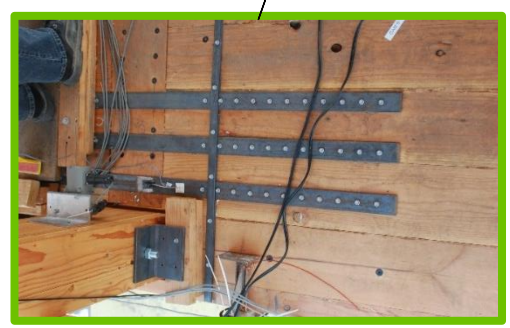


Mesh Size

(0.304 m x 0.304 m)

Linear Elastic Frame Elements
(Beams and Chord splices)

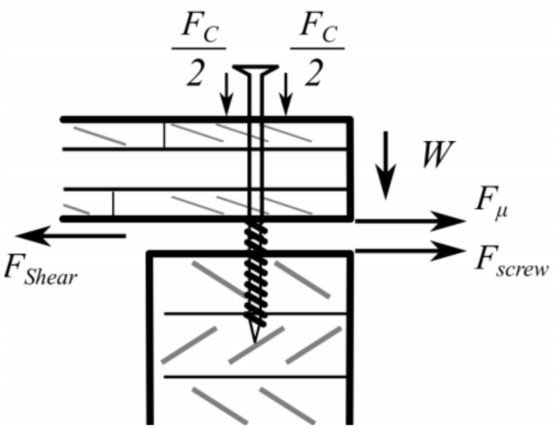
Zero-length elements
(Nonlinear Behavior)
(Surface-Splines)

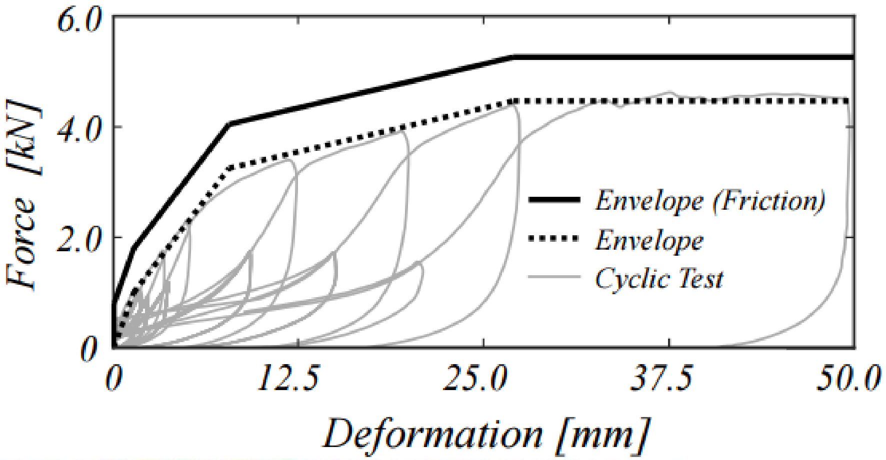


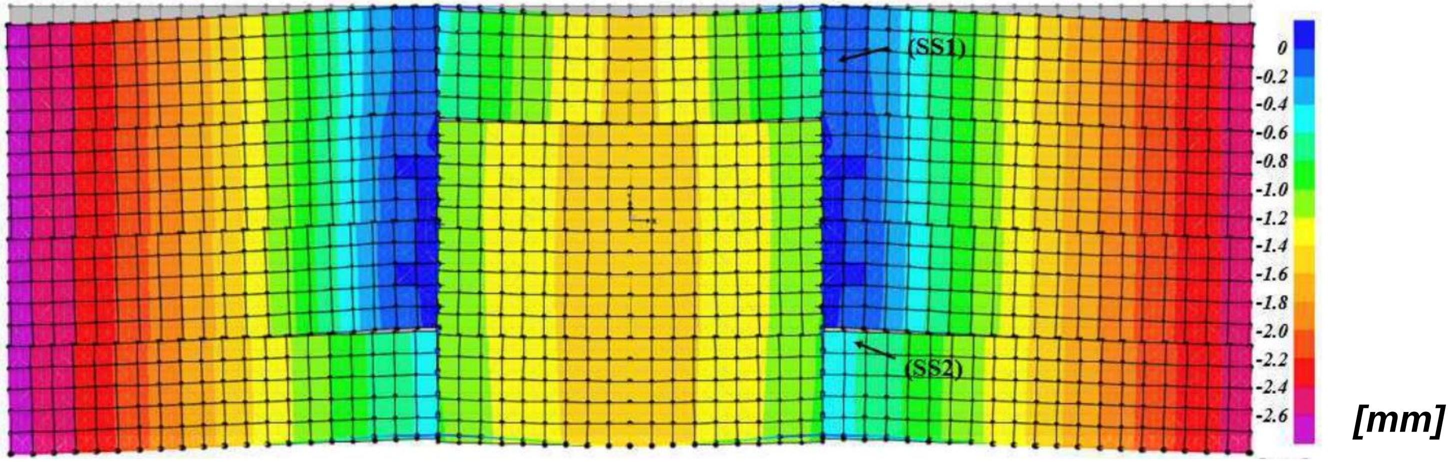
4. Shake-table test and modelling of CLT diaphragms

- Finite Element Model

SAP 2000







4. Shake-table test and modelling of CLT diaphragms

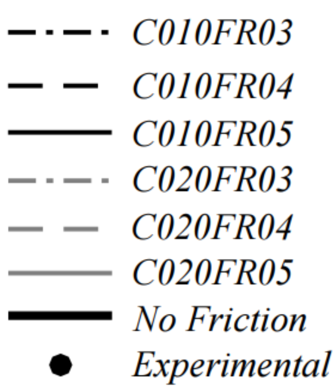
- Experimental vs FEM

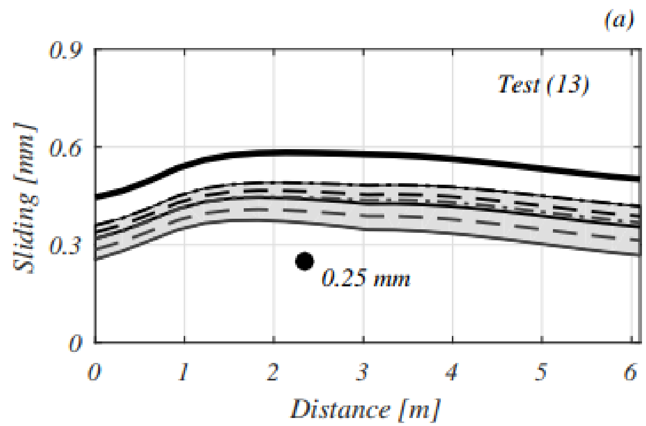
Surface splines

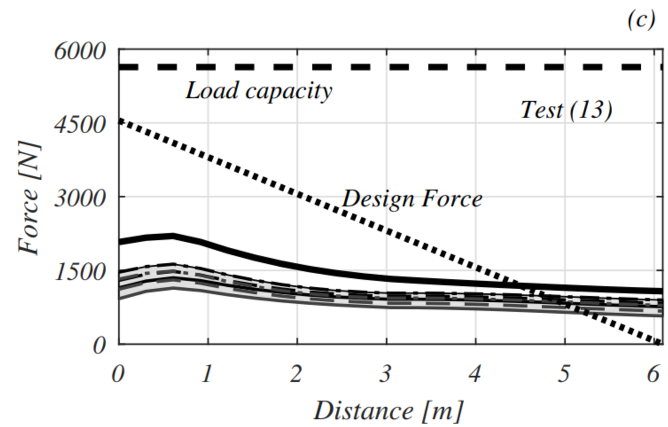
Clamping Force

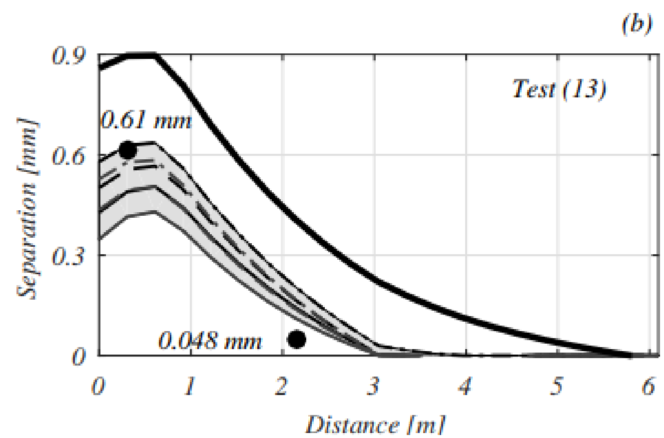
Friction Coefficient

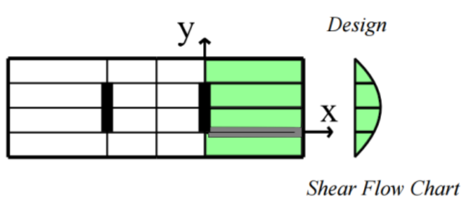
C010FR04:











Nonlinear static analysis

- Nodal Loads Proportional to Nodal Masses
- Maximum Accelerations used to compute Nodal Loads

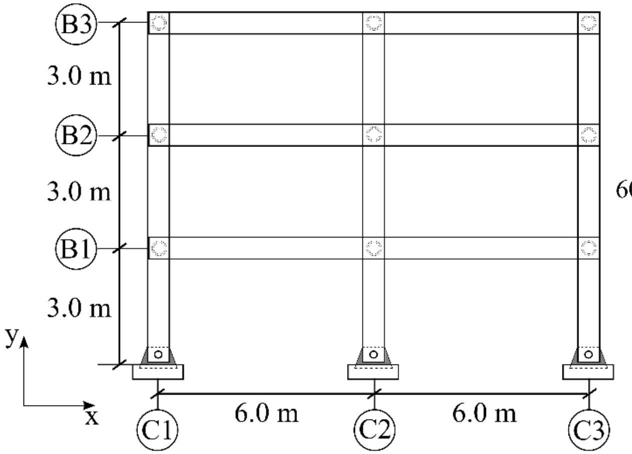
Accelerations for Northridge (MCE)
(Scale Factor 1.2 : Avg. Peak Floor Accel. (g) = 0.873)

4. Shake-table test and modelling of CLT diaphragms

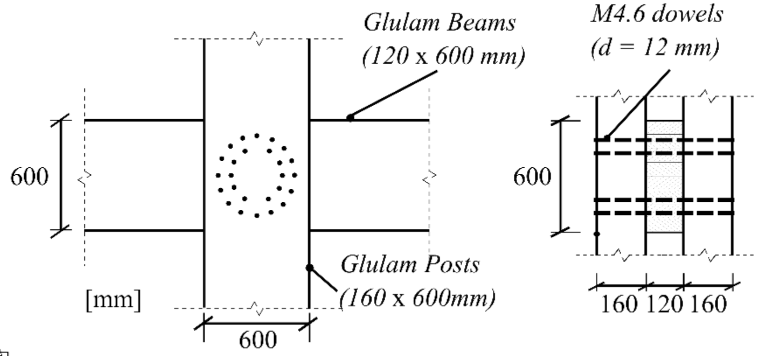
- Final Considerations
  - The Alternative Diaphragm Seismic Design Force Level of **ASCE 7-16 provides a reasonable upper bound of accelerations**, but seems to **overpredict accelerations for rocking systems.**
  - Modeling of friction is crucial to capture the surface spline deformations at all levels of excitation. **Not considering friction leads to an overprediction** of deformations in the panels, which **is acceptable for design in terms of forces in connectors and chords**. It also requires **less modelling efforts**.
  - Future studies must concentrate on keeping model reliability while **decreasing the effort expended in including crucial behaviors such as panels' closure** in surface spline connections.

5. Seismic assessment of heavy-timber structures

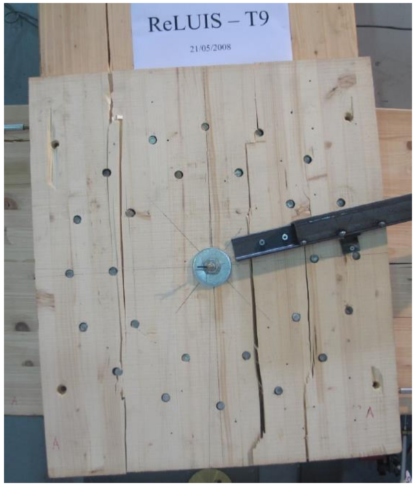
- Motivation



Moment Resisting Frame [1,2]



Details



Laboratory Testing [1,2]

- Background
  - Cyclic testing done at the connection level for ring-doweled connections
  - Design – Eurocode 8 (EC8) for a High Ductility Class (DCH), q=4.0

[1] Polastri A, Tomasi R, Piazza M, Smith I (2013) Moment resisting dowelled joints in timber structures: mechanical behaviour under cyclic tests. Ingegneria Sismica 30(4):72–81
[2] Callegari E (2009) Caratterizzazione del comportamento di telai sismoresistenti in legno lamellare. M.S. thesis, Universita` degli Studi di Trento, Trento, Italia, (in Italian)

5. Seismic assessment of heavy-timber structures

- Objectives
  - Evaluate the impact of epistemic and aleatory uncertainties on the seismic behavior of this structural system
  - Determine the q-factor for this structure type (based on pushover)
  - Develop limit state fragility functions (IDA based)

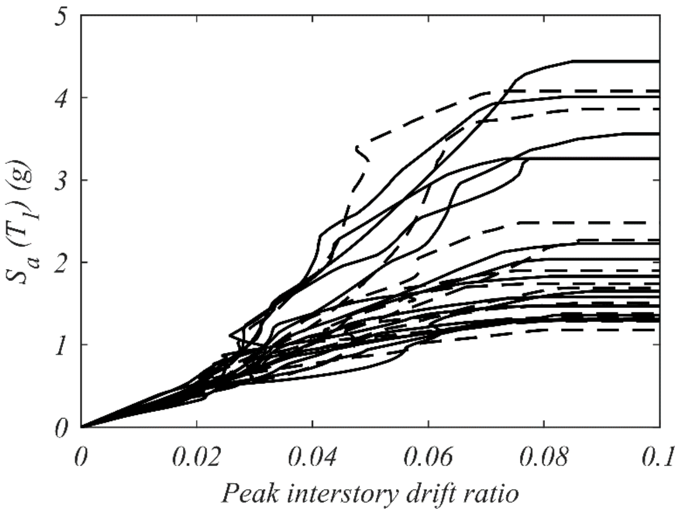
Definitions

q-factor

$$q = R_\mu \cdot R_\Omega$$

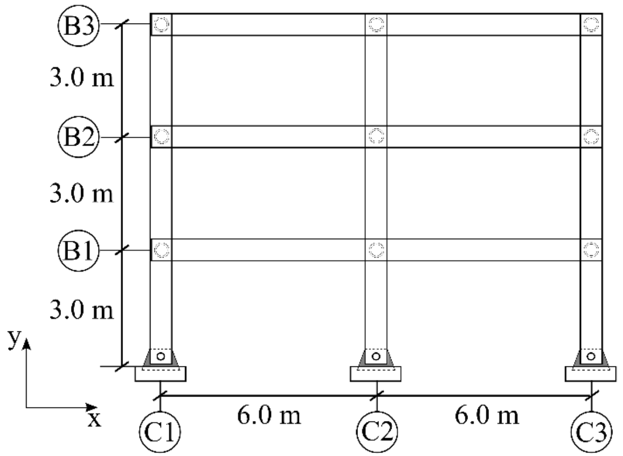
- R_μ, ductility factor
- R_Ω, overstrength factor
- q, behavior factor

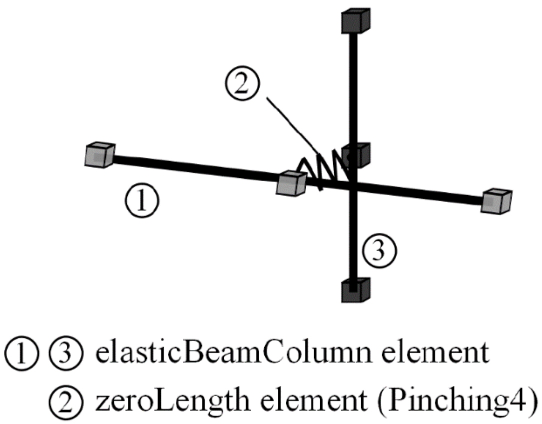
Incremental Dynamic Analysis

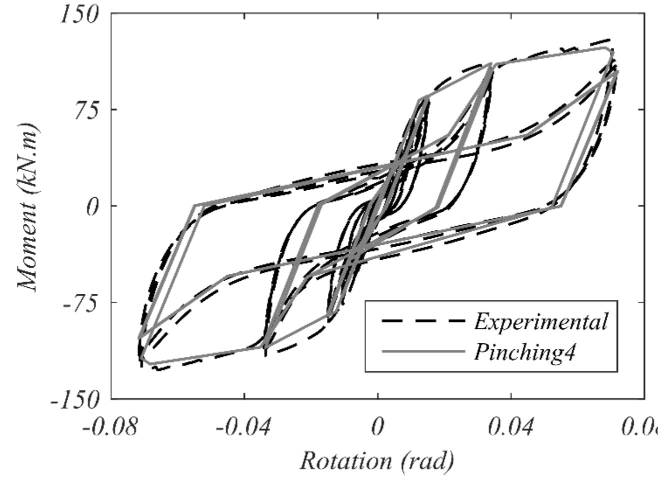


5. Seismic assessment of heavy-timber structures

- Computational Model







- Probabilistic Framework

Random Variables

- Timber properties
- Post-yielding properties of moment-resisting connections

Modeling uncertainties

- Spatial variability of members properties and connections properties

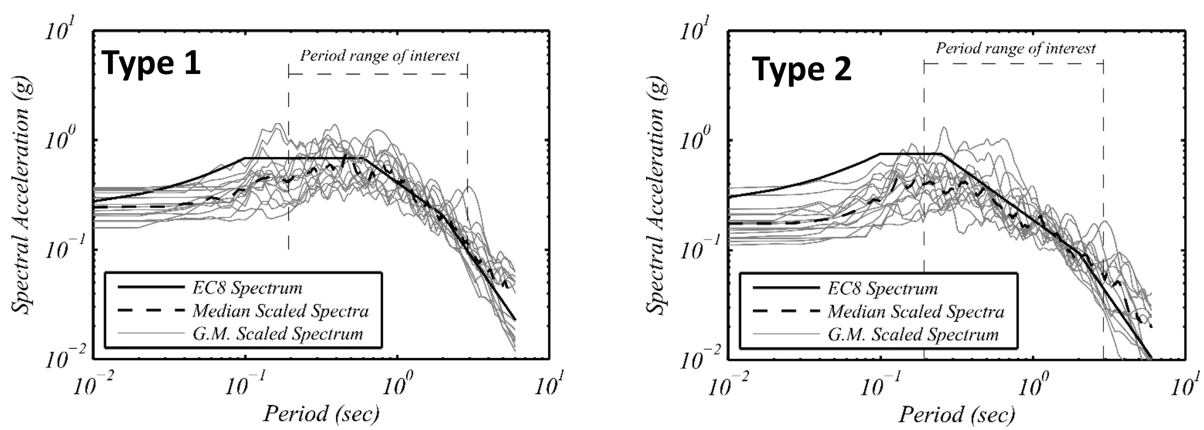
More details at:

Rodrigues, L. G., Branco, J. M., Neves, L. A., & Barbosa, A. R. (2018). Seismic assessment of a heavy-timber frame structure with ring-doweled moment-resisting connections. *Bulletin of Earthquake Engineering*, *16*(3), 1341-1371.

5. Seismic assessment of heavy-timber structures

- Analysis Performed
  - Pushover Analysis
    - First mode proportional, roof drift based
    - 1000 analyses performed (Latin Hypercube Sampling)
  - Incremental Dynamic Analysis
    - Intensity Measure: Spectral Acceleration ($S_a\ (T_1)$)
    - Demand Parameter: Peak interstory drift ratio (θ_{max})
    - Number of IDA curves generated was 24 000 (N_{IDA})

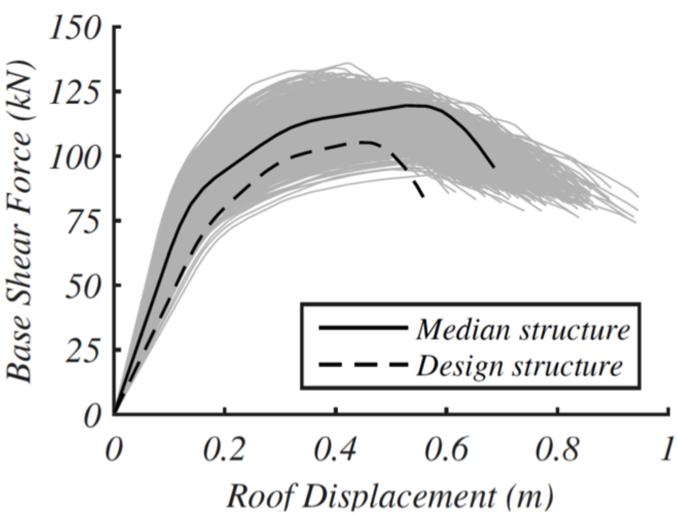
Response Spectra

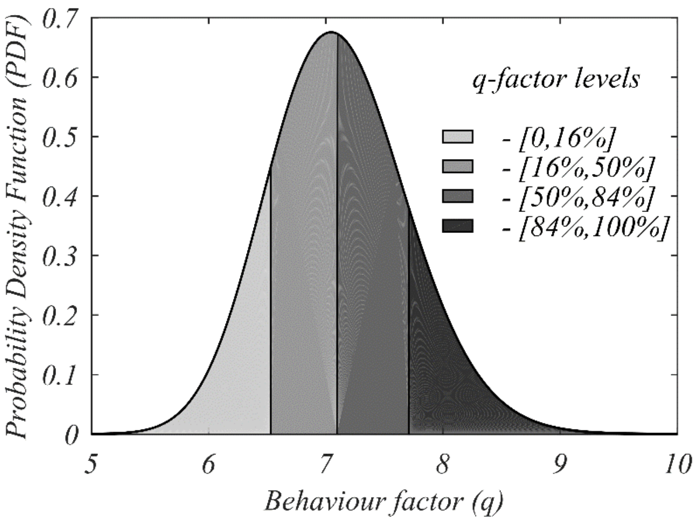


5. Seismic assessment of heavy-timber structures

- Pushover Results: q-factor
  - Remarks
    - The value assumed during the design was q = 4.0.
    - The results indicate that the detailing requirements defined in EC8 and EC5 are adequate for the design of this type of structure.

1000 nonlinear static analysis

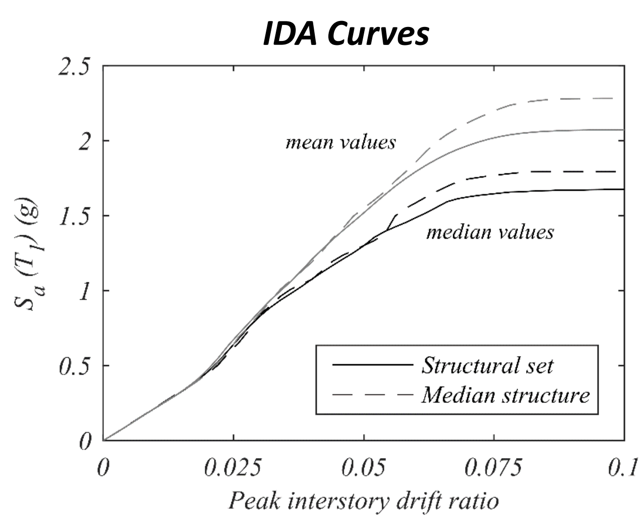


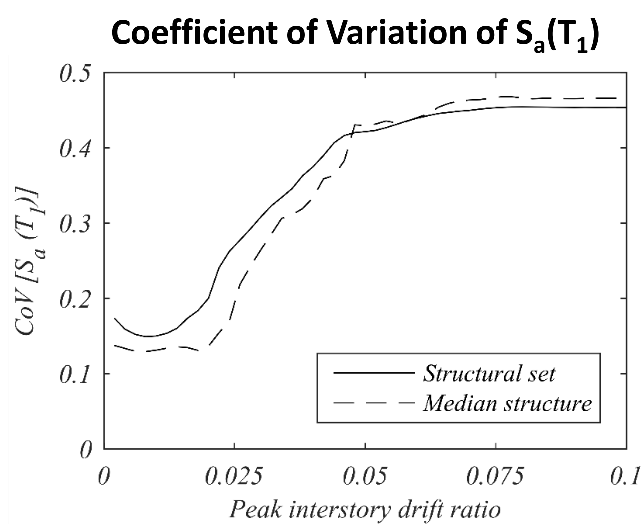


Parameter	E[X]
R_μ	4.0
R_Ω	1.8
q	7.1

5. Seismic assessment of heavy-timber structures

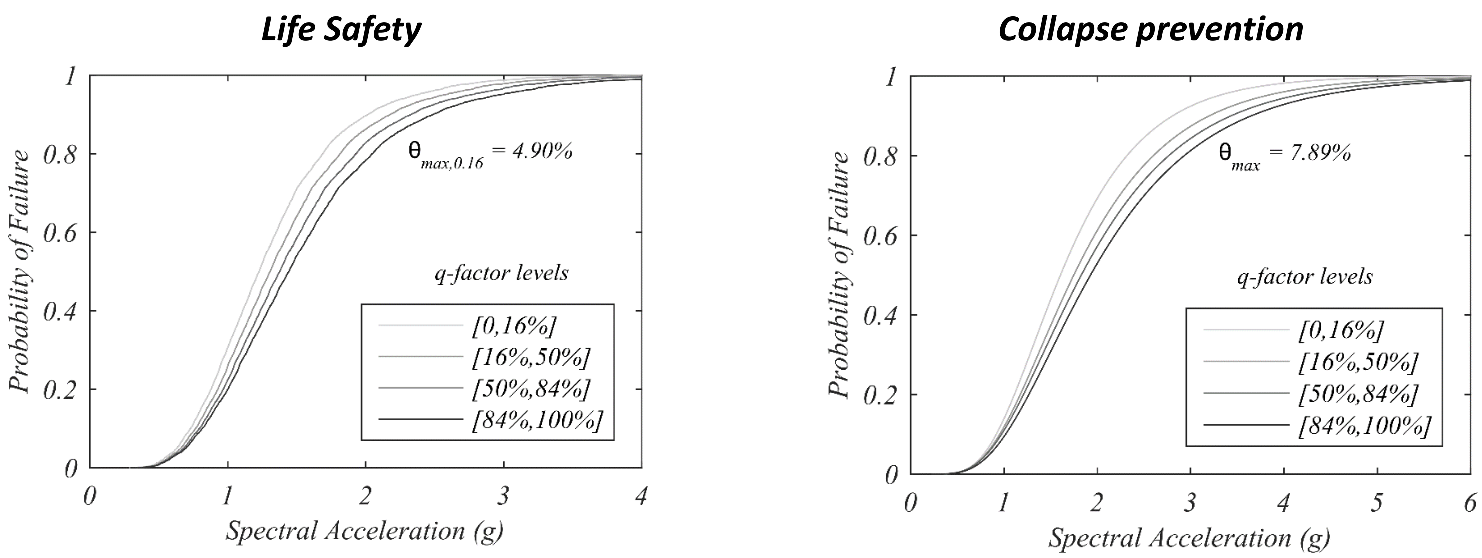
- IDA Results: *Lessons learnt*
  - **No brittle failures were observed** in the dynamic analyses conducted, indicating that the sizing **requirements in EC8 are adequate, but potentially too conservative.**
  - **Modeling uncertainties have a slight influence on the expected values** of the IDA curves (θ_{max} < 0.05). Nonetheless, the coefficient of variation increases to near 0.45.





5. Seismic assessment of heavy-timber structures

- Results: *Fragility functions*
  - From the disaggregation of the IDA curves according to four different q-factor levels, it was observed that **structural models with higher q-factors are more likely to resist ground shaking with higher intensities**, as expected.
  - The results can be partially explained due to the fact that a **positive linear correlation** of 0.46 was observed **between the q-factor and $\boldsymbol{R_{\Omega}}$**.



5. Seismic assessment of heavy-timber structures

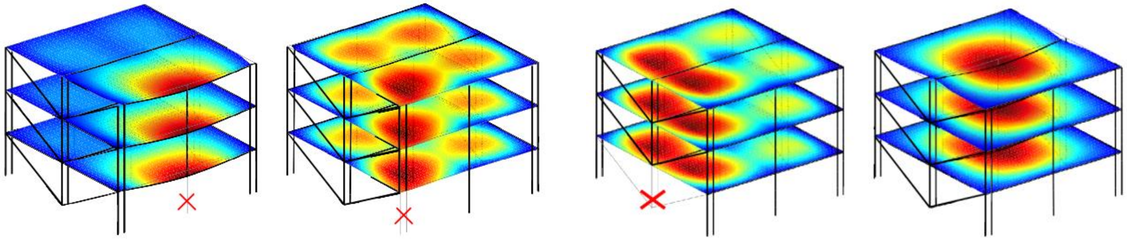
- Final Considerations
  - There is room to perform **further experimental** tests to evaluate how **a reduction of connected elements thickness**, and **slenderness of dowels**, would impact the behavior of the moment resisting connections.
  - **New tests** would also allow to **characterize uncertainty of the expected model parameters used in design** and their correlation with observed joint performance.
  - Such tests, along with the methodology proposed, could contribute to **propose new design values and detailing requirements to heavy-timber frame structures**.

More details at:

Rodrigues, L. G., Branco, J. M., Neves, L. A., & Barbosa, A. R. (2018). Seismic assessment of a heavy-timber frame structure with ring-doweled moment-resisting connections. *Bulletin of Earthquake Engineering*, *16*(3), 1341-1371.

6. Robustness assessment of heavy-timber structures

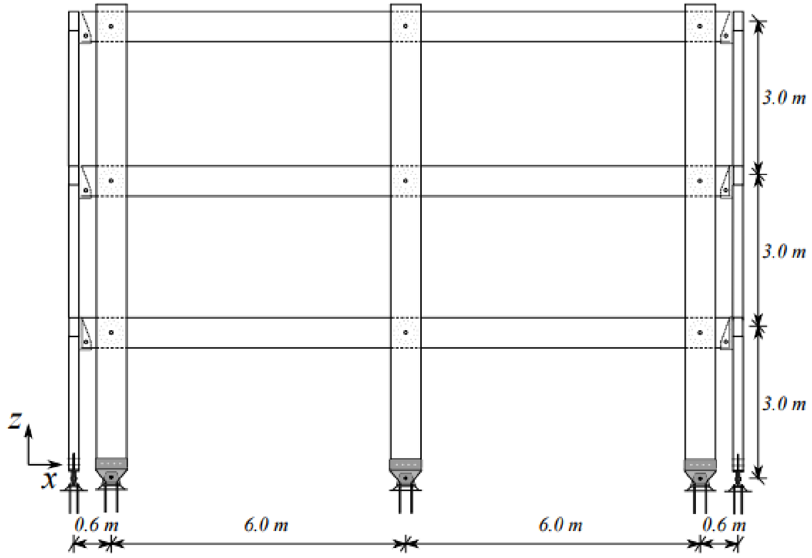
- Objectives
  - Present a **progressive collapse assessment** of a heavy-timber structure **designed to fulfill the requirements of seismic provisions** in terms of member sizing and connections ductility.
  - Given **the importance of diaphragms to trigger alternative load paths**, develop fragility functions for two distinct floor solutions: **CLT panels** connected with half-lap joints, and a low weight solution with **OSB panels** and glulam joists.



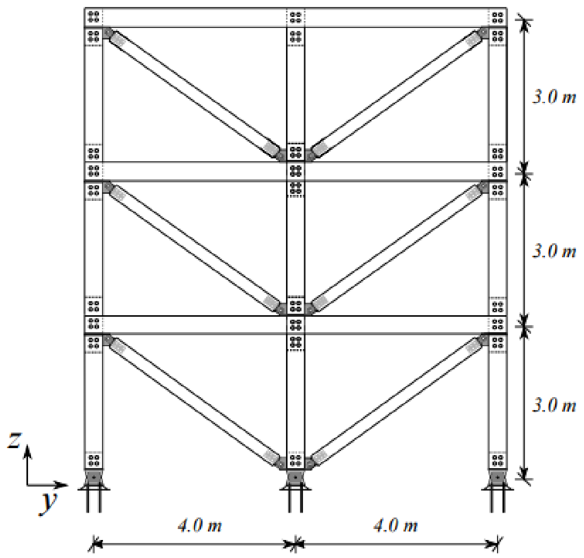
This evaluation considers **material and loading variability** and the application of the **alternative load path method** that has been widely applied to steel structures.

6. Robustness assessment of heavy-timber structures

- Design
  - Moment-resisting frame
    - Eurocode 8 (EC8) for a High Ductility Class (DCH), *q=4.0*
  - Braced timber frame
    - Eurocode 8 (EC8) for a High Ductility Class (DCH), *q=2.0*



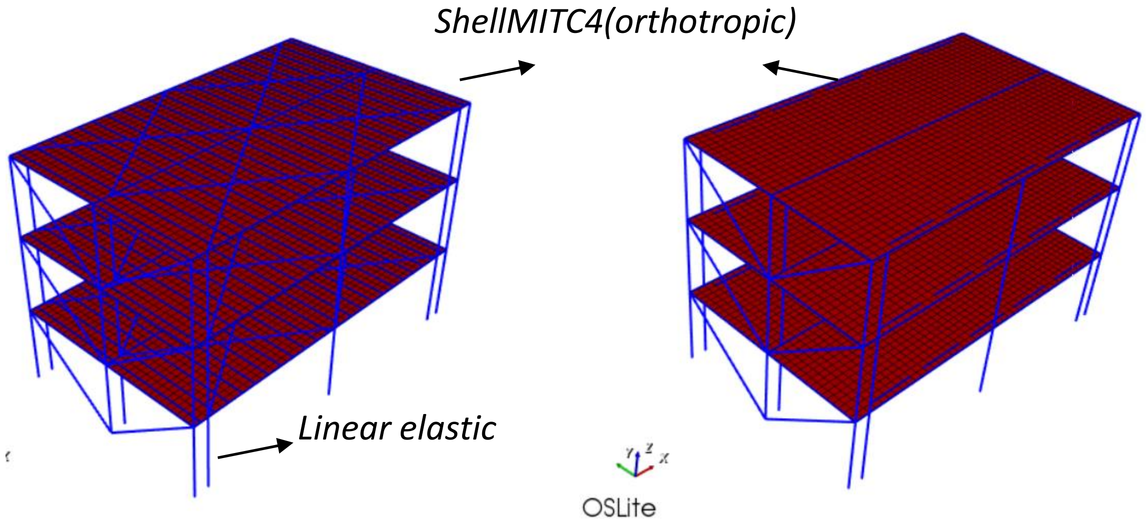
(a) Moment-resisting frame: elevation



(b) Braced timber frame: elevation

6. Robustness assessment of heavy-timber structures

- Computational model (3D model)



(a) OSB Diaphragms (b) CLT Diaphragms

- P-delta effects for columns
- Corotational transformation for beams
- Four node shell elements (panels)

Force-deformation relationships of connections were incorporated considering **experimental results available in the literature**.

- Probabilistic framework

<u>**Random variables**</u>

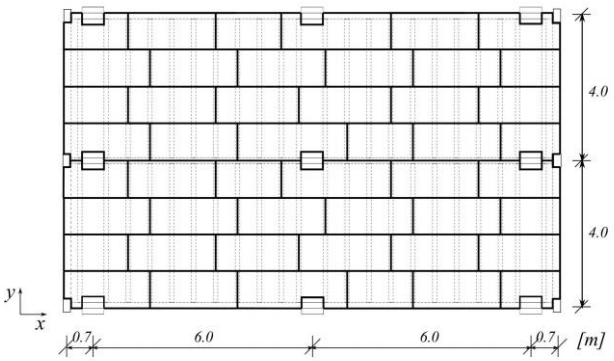
- Timber properties
- Moment-resisting joints
- Steel-to-timber joints
- CLT to Glulam beams
- Joist-to-beams

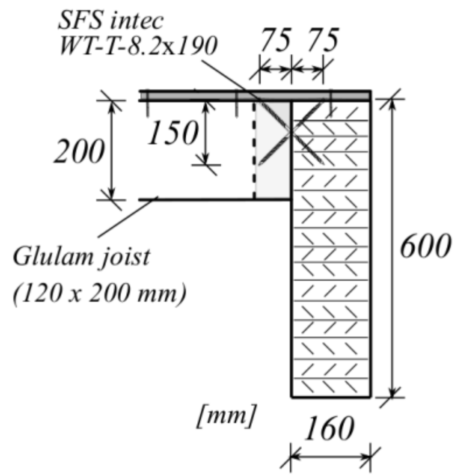
Latin Hypercube Sampling

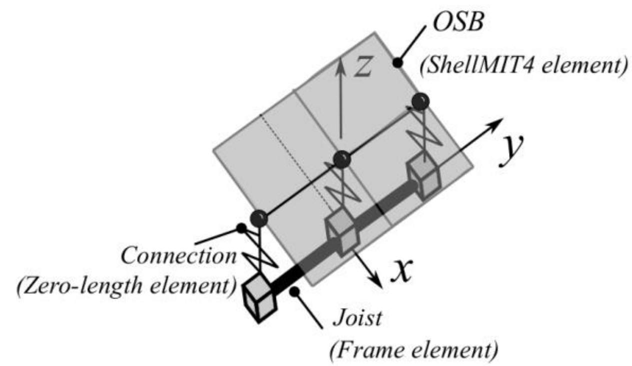
6. Robustness assessment of heavy-timber structures

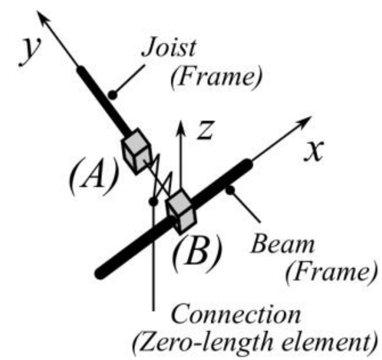
- Modelling details

  - Light-frame

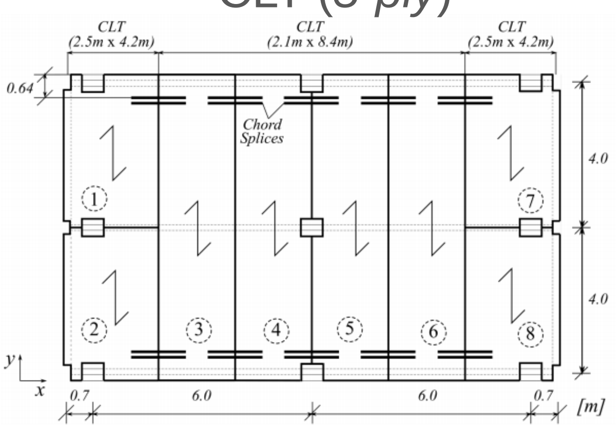


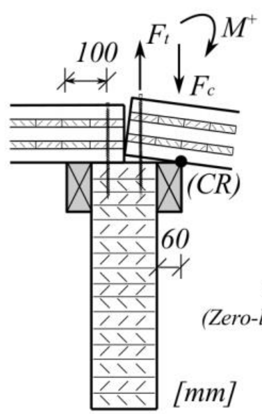


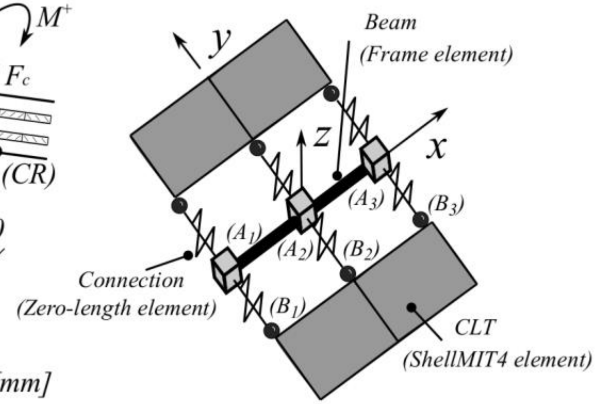




  - CLT (*5-ply*)







6. Robustness assessment of heavy-timber structures

- Alternative load path method
  - Design load combination (UFC 4 -023-03)

$$G = \Omega \; \boxed{[1.2D + 0.5LL]} \rightarrow G_n$$

Dynamic amplification factor

Dead Load

Live Load

*For timber structures that **Ω** = 2.0 (ARUP,2011)*

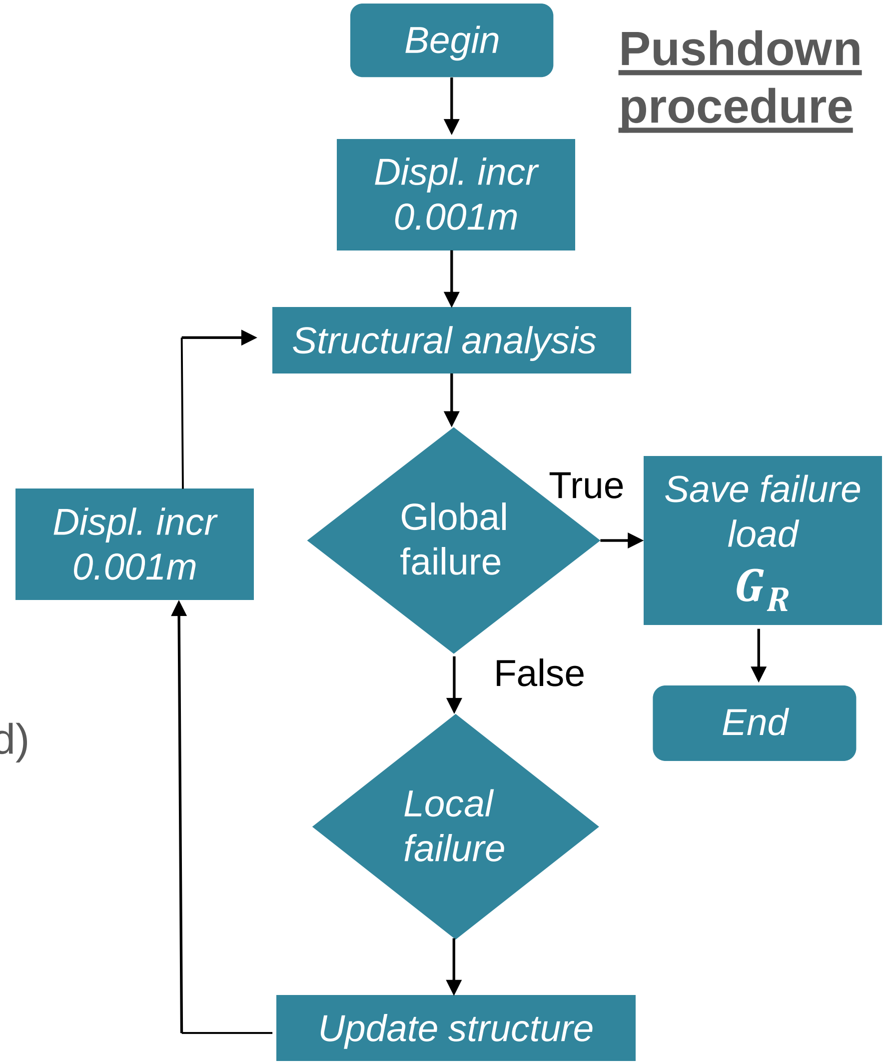
- Pushdown analysis
  - Notional removal of elements (Damage)
  - Nonlinear static analyses (Displ. controlled)

Failure Load

Overload Factor $\leftarrow \; OF = \dfrac{G_R}{G_n}$

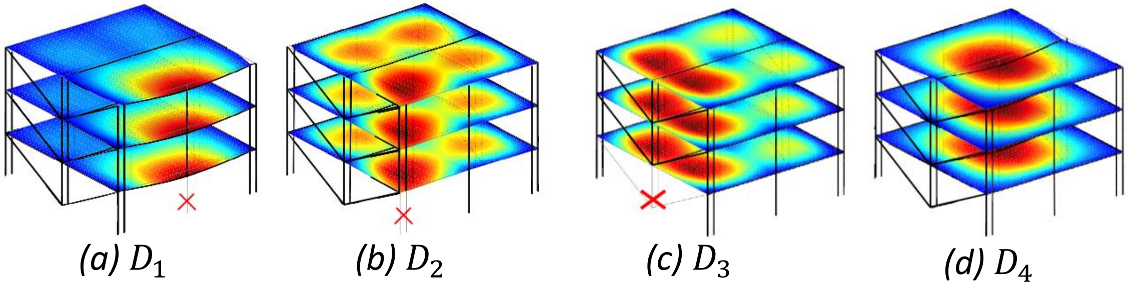
Nominal Load

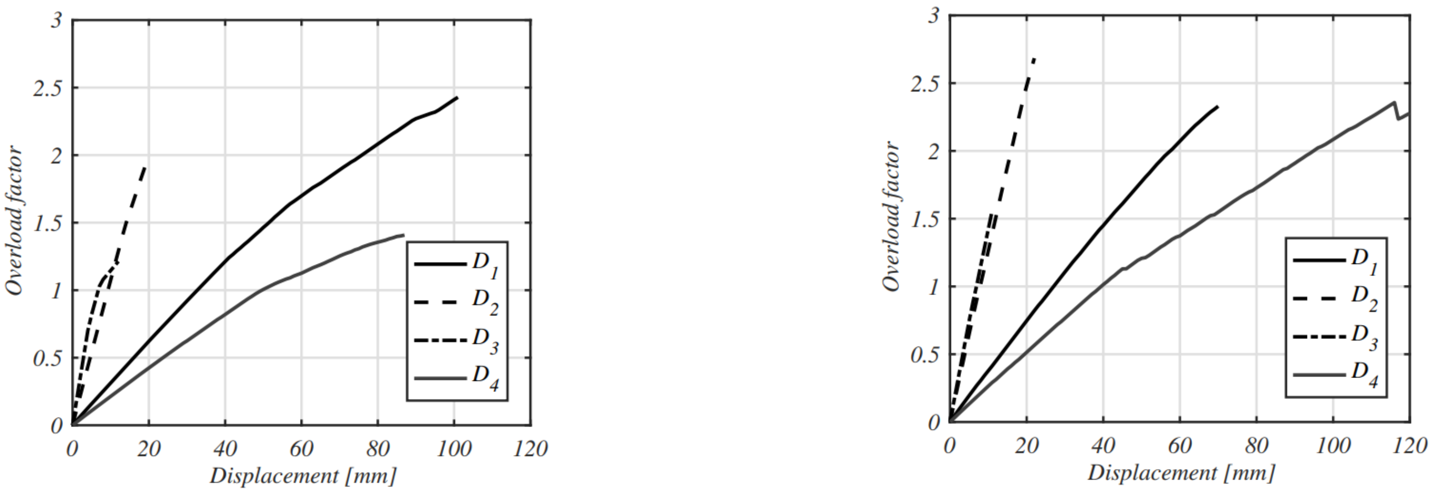
Pushdown procedure



6. Robustness assessment of heavy-timber structures

- Pushdown curves





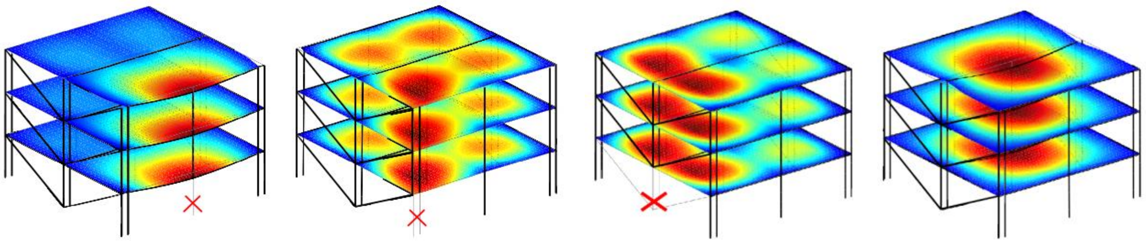
(a) OSB diaphragm

(b) CLT diaphragm

Since CLT panels are continuous at the center of the structure, the respective analyses presented higher overload factors than the ones performed for structures built with light-frame diaphragms.

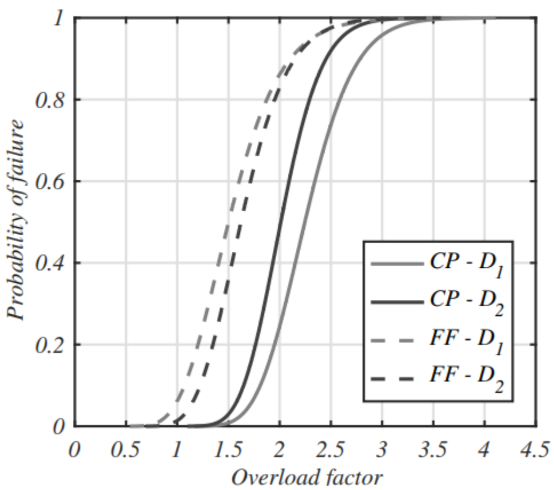
6. Robustness assessment of heavy-timber structures

- Fragility curves
  - Light-frame diaphragm

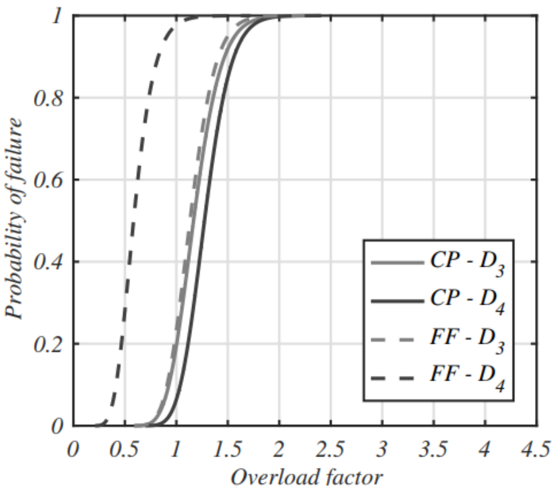


(a) D_1 (b) D_2 (c) D_3 (d) D_4

$$P(C) = \boldsymbol{P(C|D)} \cdot P(D|E) \cdot P(E)$$



(a) External frame

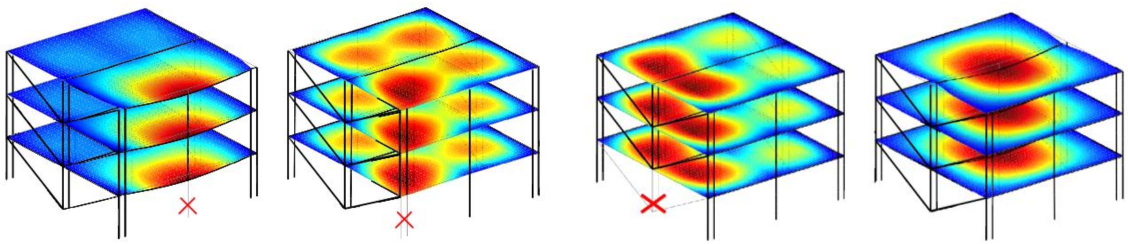


(b) Internal frame

The light-frame diaphragm showed a low capacity to redistribute loads, particularly for damage scenarios D_3 and D_4 that imposed higher load levels on glulam beams.

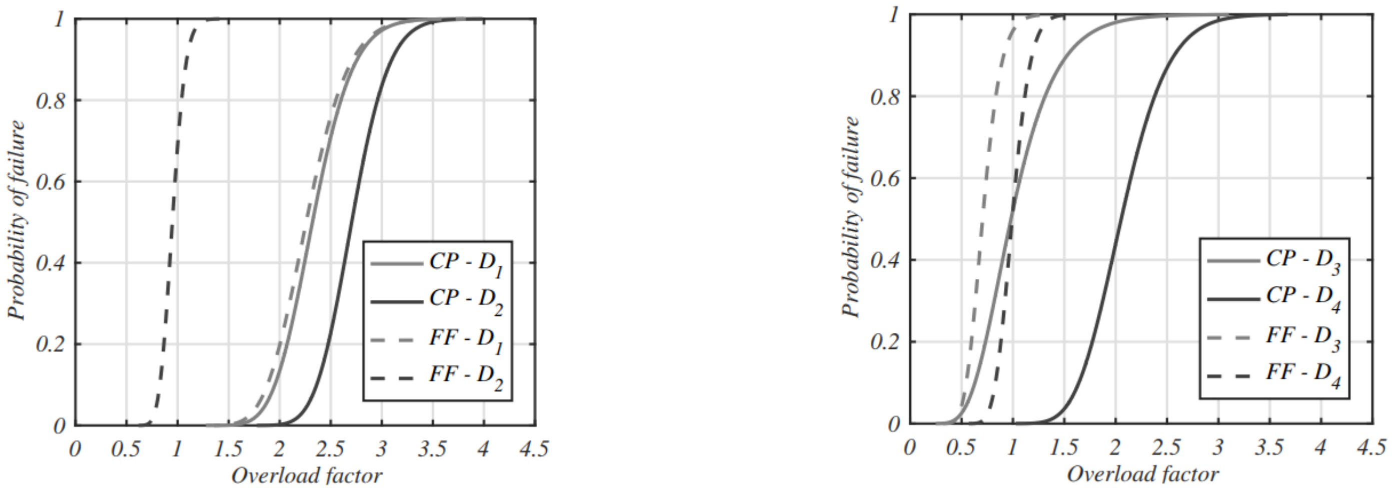
6. Robustness assessment of heavy-timber structures

- Fragility curves
  - CLT diaphragm



(a) D_1 (b) D_2 (c) D_3 (d) D_4

$$P(C) = \boldsymbol{P(C|D)} \cdot P(D|E) \cdot P(E)$$



(a) External frame (b) Internal frame

The continuity of CLT panels over two bays increased the ability of the structural system to redistribute loads.

6. Robustness assessment of heavy-timber structures

- Final Considerations
  - The **seismic design provisions used to define elements** sizing and connections geometrical configurations **do not dismiss a progressive collapse assessment** during the design phase.
  - It is **important to consider the different type of diaphragms** that can be used to built structures, as well as **distinct initial damage scenarios**. From the results obtained, **CLT diaphragms present lower conditional probabilities of failure than light-frame diaphragms**, for overload factors equal to 2.0.
  - In the future, **monotonic and cyclic tests should be performed to confirm the results** presented in this work, since **modelling uncertainties are associated to the strength and stiffness** of floor-to-frame connections.

7. Conclusions and Future developments

- Risk Assessment
  - The **methodologies presented to generate fragility curves can be included on a risk based robustness assessment**, which shall consider the probabilities of occurrence of different exposures, such as earthquakes, impacts and explosions, and the direct and indirect consequences of structural failures.

- Experimental campaign survey
  - It is crucial to **develop a database able to aid practitioners to model properly the nonlinear behavior of connections**. Such tool will definitely **decrease the uncertainties** related to numerical modeling and allow to **detect the gaps in knowledge** that need to be filled (e.g. rotational strength and stiffness of floor-to-frame connections).

7. Conclusions and Future developments

- **TimQUAKE** - Structural performance of timber joints and structures under earthquake (POCI-01-0145-FEDER-032031), co-financed by the European Regional Development Fund (ERDF), through the Operational Programme for Competitiveness and Internationalization (COMPETE 2020), under Portugal 2020, and by the Fundação para a Ciência e a Tecnologia – FCT I.P.

  – The main objective of this research project is to **define synthetic laws for the cyclic behavior of common dowel-type connections** used in timber structures. It will be possible **to provide guidelines to practitioners** that aim to **perform static and dynamic nonlinear analysis of timber structures**, located in seismic regions, releasing them from the performance of cyclic tests (according to EN 12512), which are currently needed to validate the numerical models used.

Acknowledgments

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