ROBUSTNESS OF MULTI-STOREY TIMBER BUILDINGS

Recent and future developments of the PhD programme

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Topics

1. Introduction
2. Seismic assessment of a heavy-timber frame structure
3. Current and future developments
4. Design and modeling of CLT and CLT-Concrete Floor Diaphragms (Shake-Table Testing at UCSD)

Introduction

- How seismic design provisions influence the robustness of multi-storey timber buildings?

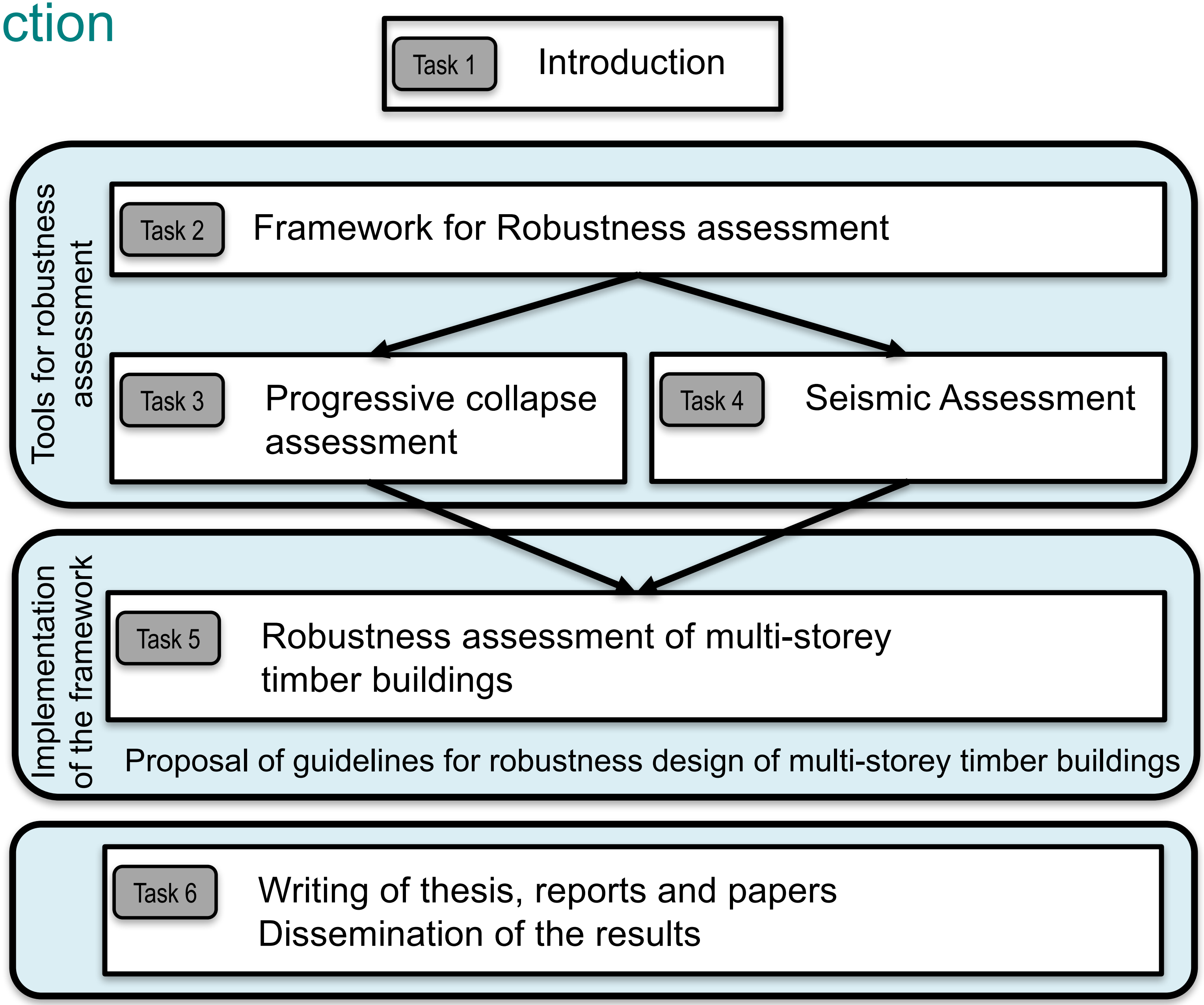
Seismic design provisions

- Simplicity;
- Uniformity;
- Symmetry;
- Redundancy;
- Bi-directional strength and stiffness;
- Torsional resistance and stiffness;
- Diaphragmatic behavior at the storey level;
- Adequate foundations;

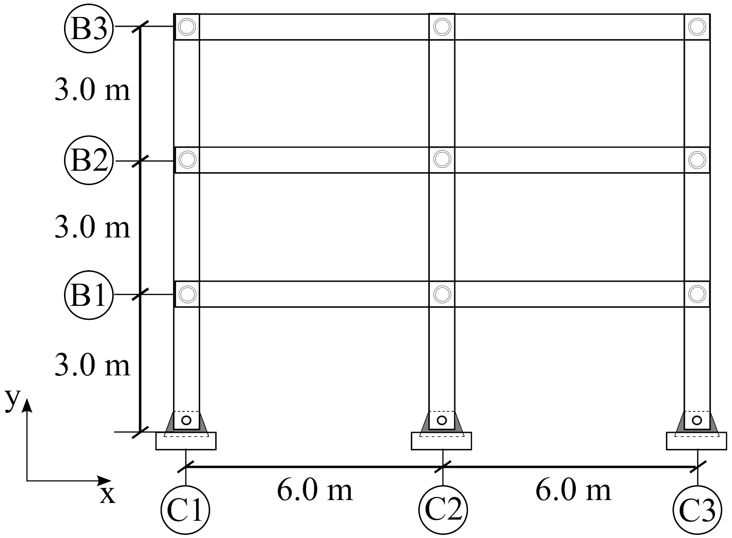
Robustness design recommendations

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

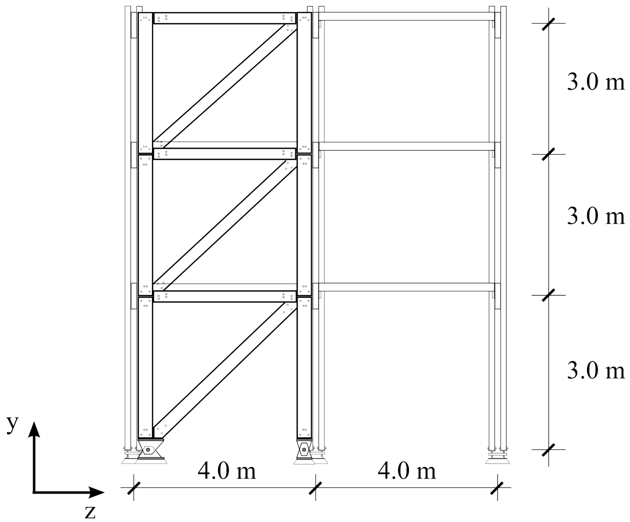
Introduction



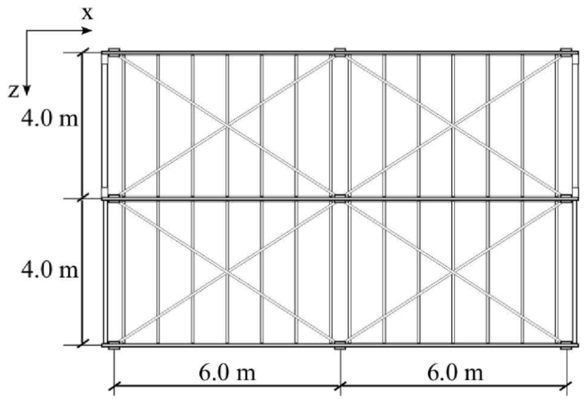
Seismic assessment of a heavy-timber structure



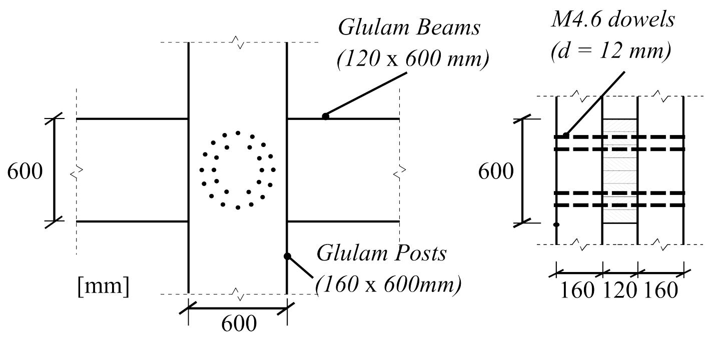
(a) Elevation – Moment Resisting Frame



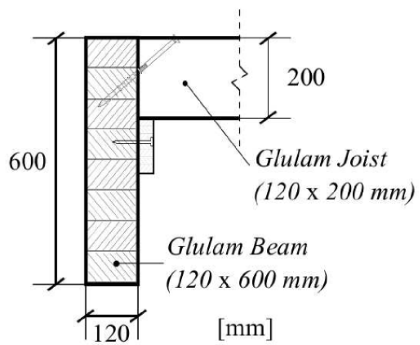
(b) Elevation – Braced Timber Frames



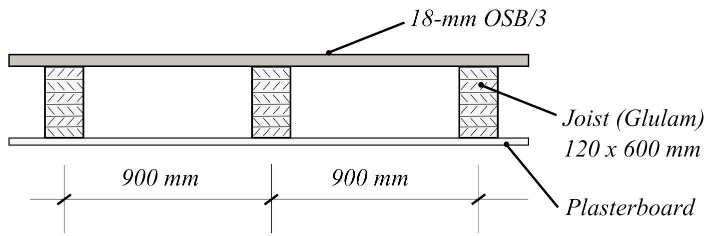
(c) Floor Plan



(d) Ring-doweled connections



(e) Joists to Beam connections



(f) Timber floor – OSB nailed to glulam joists

Seismic assessment of a heavy-timber structure

Objectives

- Characterize behavior factor *q*
- Definition of interstory drift limit states
- Development of fragility functions for different damage state levels

Probabilistic Framework

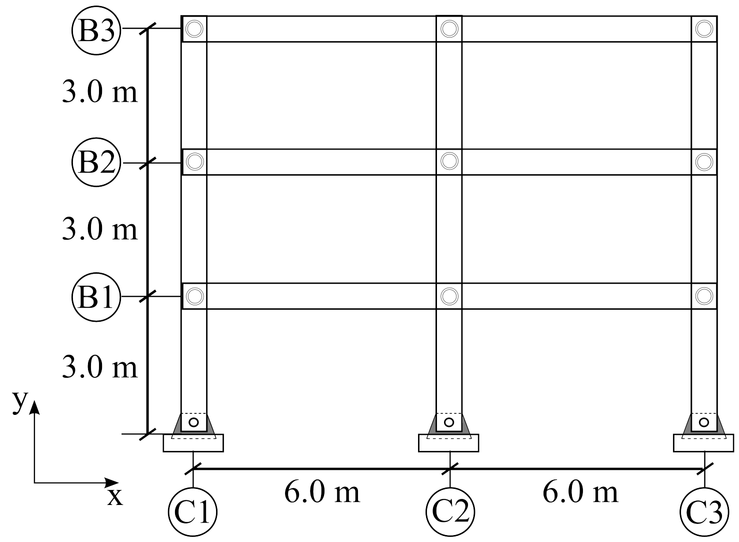
Latin Hypercube Sampling used to generate analytical models of the structure

Random Variables

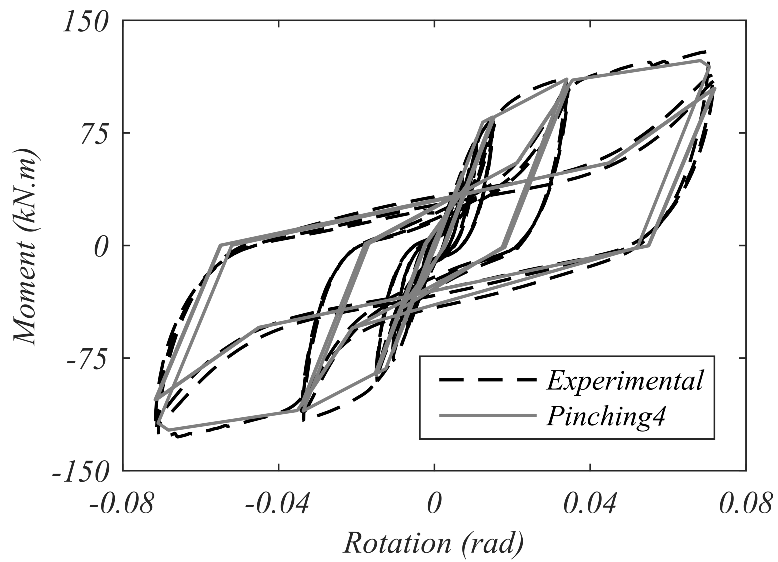
- Timber properties
- Post-yielding properties of moment-resisting connections

Modeling uncertainties

Spatial variability of members properties and connections properties

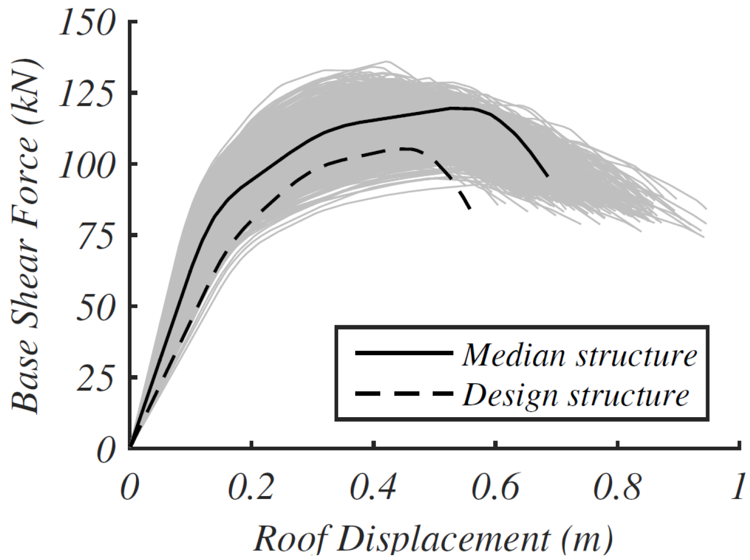


(a) Elevation – Moment Resisting Frame

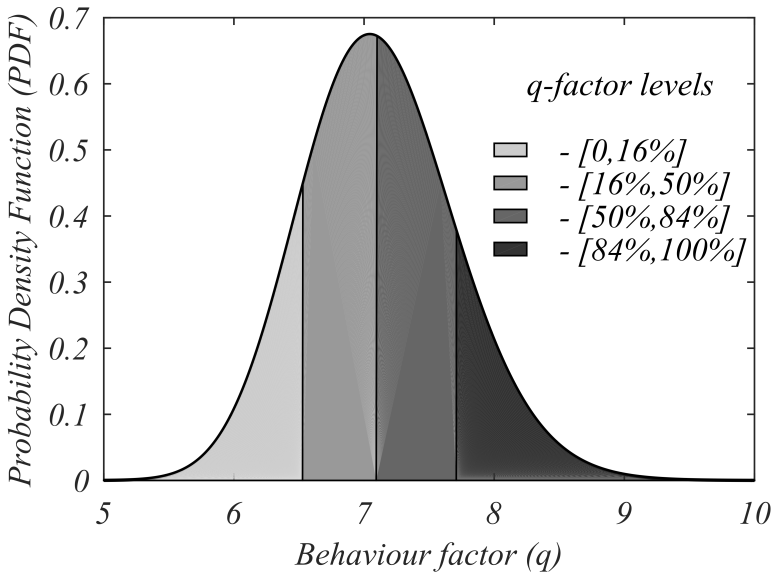


(b) Meso-level connections models (Pinching4)

Seismic assessment of a heavy-timber structure



(a) Capacity Curves



(b) q-factor levels and fitted PDF

Pushover analysis

- 1000 Nonlinear static analysis performed
- Parameters for the peak value of interstory drift ratio θ_{max} were obtained:
  - Immediate occupancy (E[X]=1.2%; CoV = 0.09)
  - Life-Safety (E[X]=4.9%; CoV = 0.14)
  - Collapse Prevention (E[X]=8.0%; CoV = 0.11)

q-factor estimations

According to Fajfar et al (1999) the q-factor is given by:

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

- R_μ, ductility factor (E[X]=4.0; CoV = 0.08)
- R_Ω, overstrength factor (E[X]=1.8; CoV = 0.06)
- q, behavior factor (E[X]=7.1; CoV = 0.08)

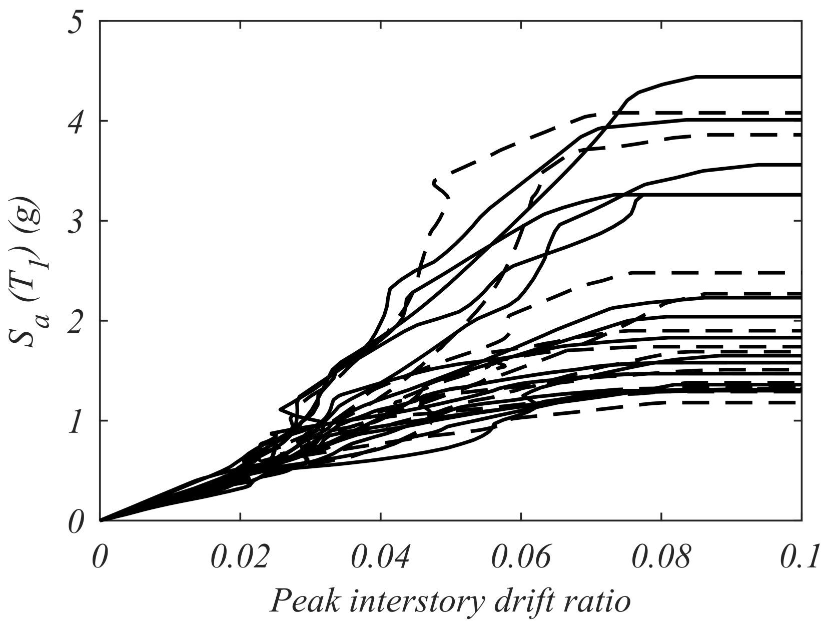
Remarks

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.

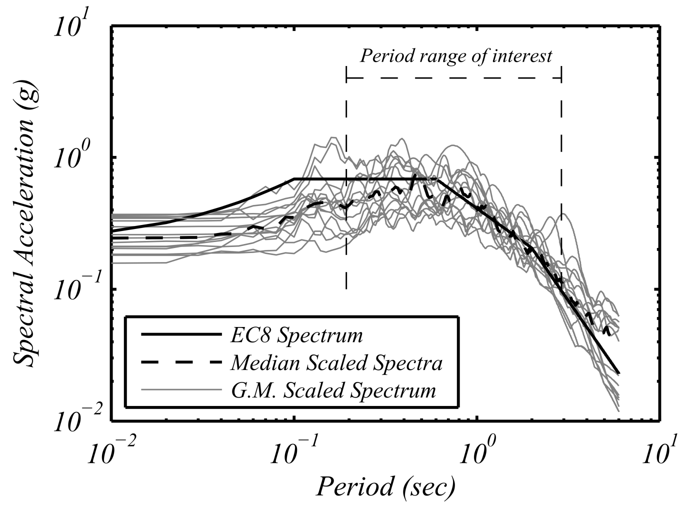
Seismic assessment of a heavy-timber structure

Multi-Record Incremental Dynamic Analysis

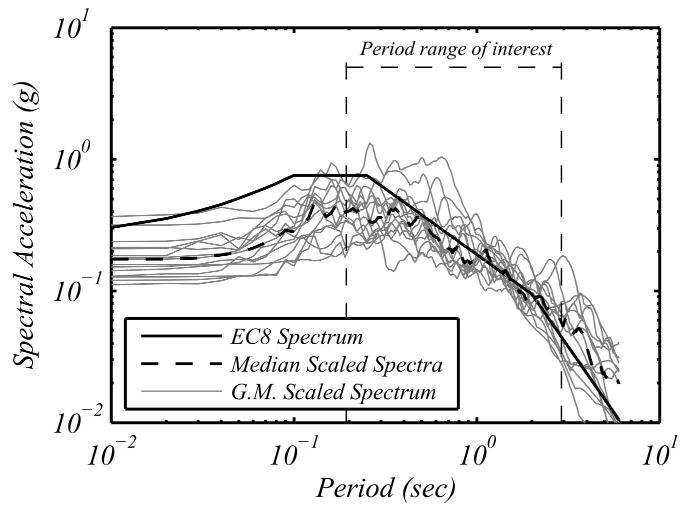
- Intensity Measure: Spectral Acceleration ($S_a(T_1)$)
- Demand Parameter: Peak interstory drift ratio (θ_{max})
- The number of IDA curves is equal to 24000 (N_{IDA}) resulting on 720000 nonlinear dynamic analyses.
- A sequential version of **OpenSees** and a batch-queue system called **HTCondor (v7.8.0)** was used



(a) Single-record IDA Curves: Median Structure



(b) Response Spectra – Type 1



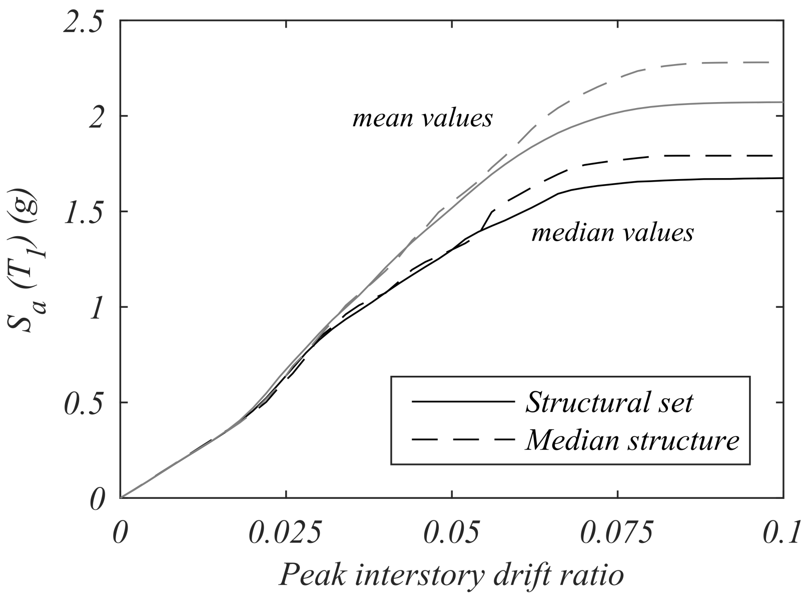
(c) Response Spectra – Type 2

Seismic assessment of a heavy-timber structure

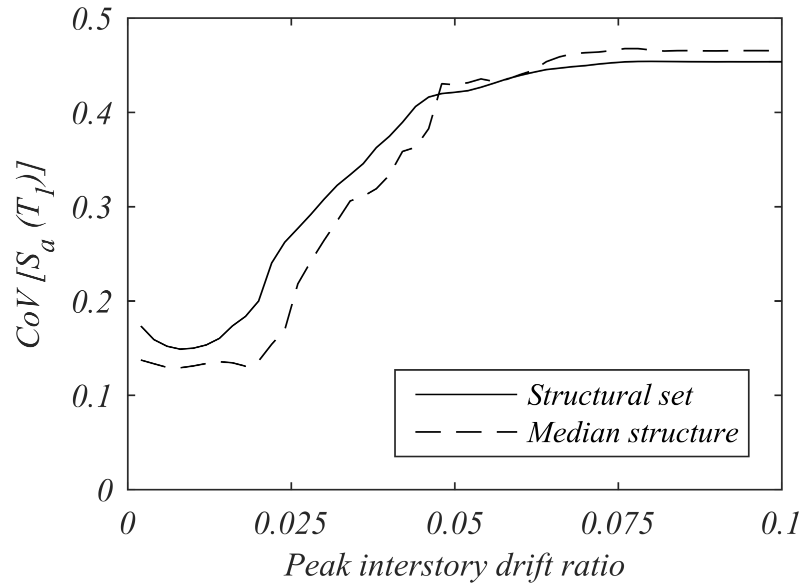
Multi-Record IDA Results:

- Modeling uncertainties have a slight influence on the expected values of the IDA curves ($\theta_{max} < 0.05$). Nonetheless, the coefficient of variation increases up to 43% more.

- No brittle failures were observed in the dynamic analyses conducted, indicating that the sizing requirements in EC8 are adequate, but potentially too conservative.



(a) Mean and Median IDA curves

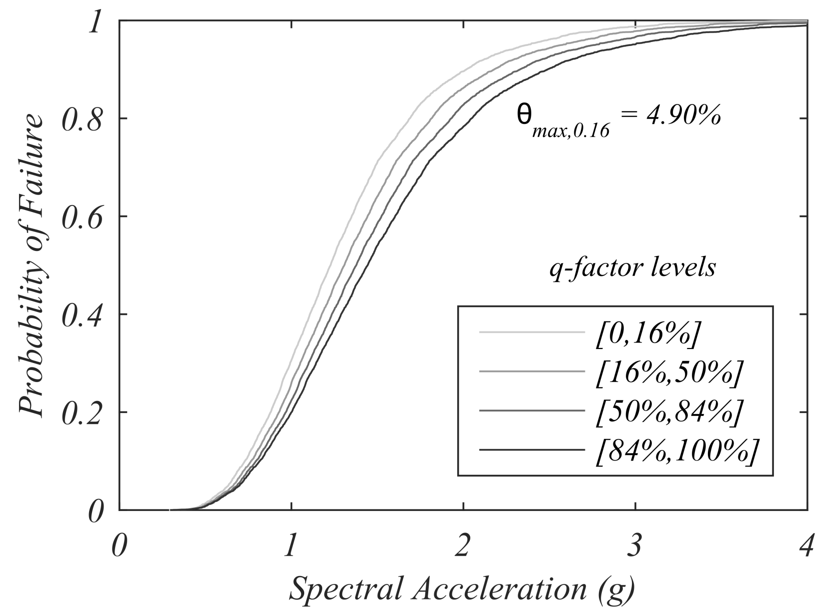


(b) Coefficient of Variation of Sa(T1)

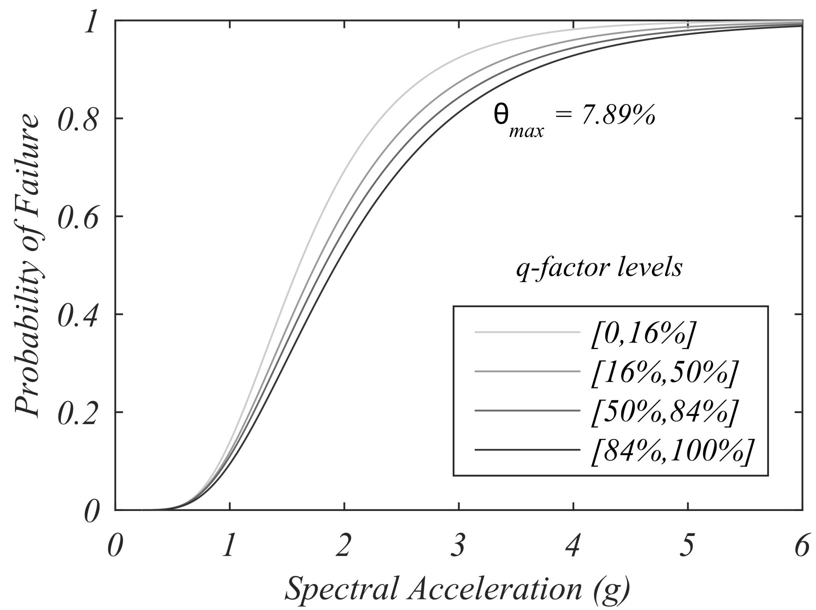
Seismic assessment of a heavy-timber structure

Fragility functions for different q-factor levels

- 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.
- 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 R_{Ω}.



(a) Life Safety

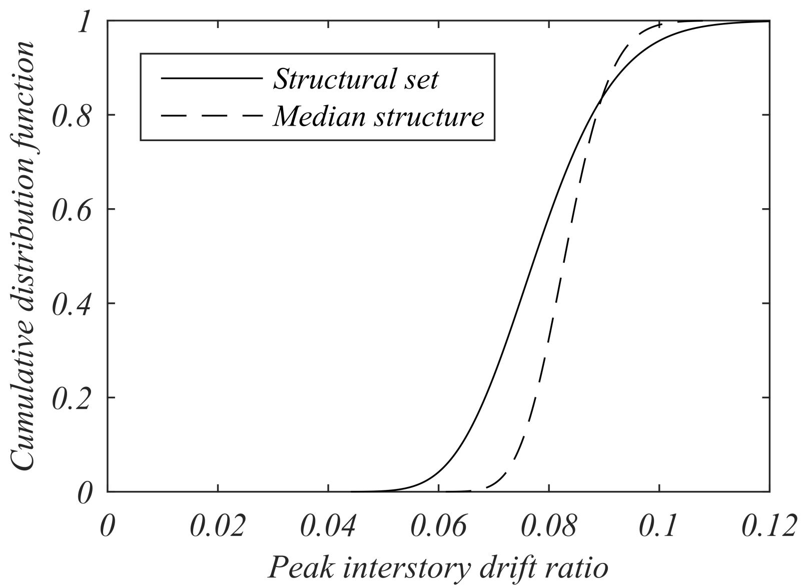


(b) Collapse Prevention

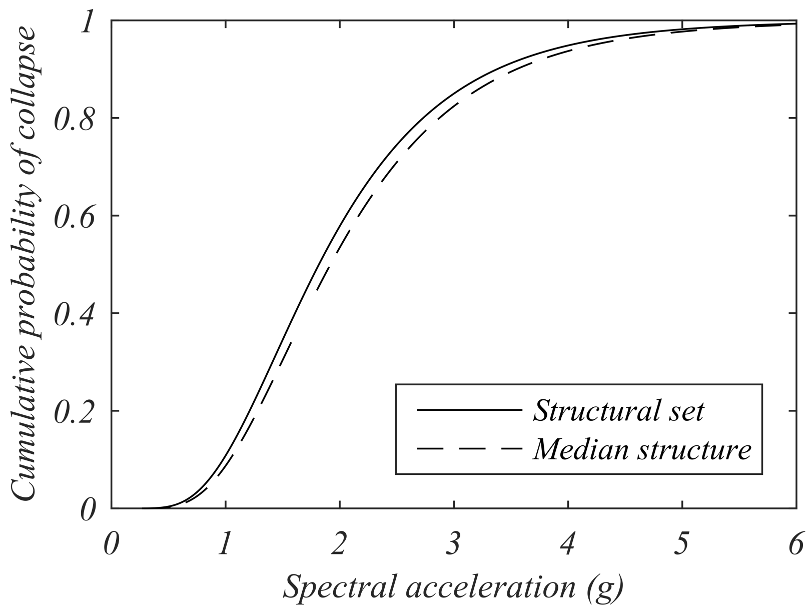
Seismic assessment of a heavy-timber structure

Global Collapse fragility curves

- When modeling uncertainties are neglected an overestimation of the capacity is obtained, both in terms of spectral acceleration and peak interstory drift ratio.



(a) Peak-interstory drift



(b) Spectral acceleration

Seismic assessment of a heavy-timber structure

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.

- Such tests, along with the methodology proposed, could contribute to propose new design values and detailing requirements to heavy-timber frame structures.

- New tests would also allow to characterize uncertainty of the expected model parameters used in design and their correlation with observed joint performance.

Current and future developments

Seismic assessment

- Development of non-linear finite element models to analyze the case-study building under more complex conditions, requiring a full 3D model.
- This comprises the design and modeling of **two different solutions for lateral resisting** system. Namely, braced timber frames and CLT shear walls.
- **Three different solutions will be considered for the floors**, namely: OSB panels attached to secondary beams, CLT panels with surface spline joints and a composite CLT-concrete solution.

Progressive collapse assessment

- In order to obtain a correlation between seismic performance and propensity to **progressive collapse**, the structural models studied in the previous point will be subjected to **pushdown analysis** to **simulate sudden column's loss**.
- **Fragility curves** will be developed considering **material and loading uncertainties** for different limit states related to vertical displacements, partial collapse and global collapse.

Current and future developments

Workplan of the PhD programme

Task	2016						2017												2018							
	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
1 – Introduction (100%)																										
2 – Framework for Robustness assessment (100%)																										
3 – Seismic Assessment (60%)																										
4 – Progressive collapse assessment (40%)																										
5 - Implementation of the framework (0%)																										
6 – Writing of thesis, reports and articles (30%)																										

(1) **(2)** **(WCTE)** **(3)**

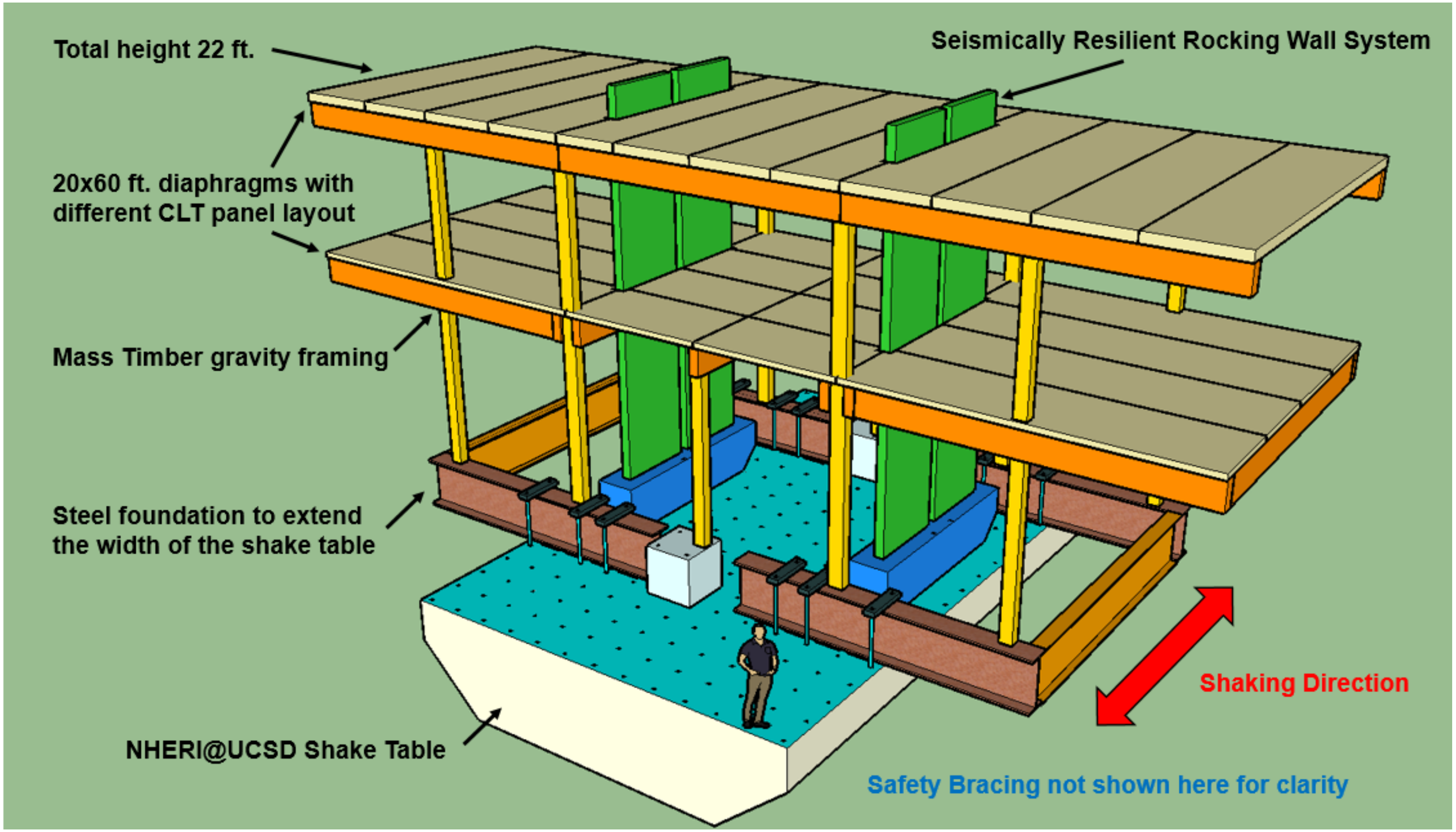
(1) Rodrigues LG, Branco JM, Neves LAC, Barbosa A (2017) Seismic Assessment of a Heavy-Timber Frame Structure with Ring-Doweled Moment-Resisting Connections. Bulletin of Earthquake Engineering (accepted with revisions)

(2) Journal Paper Submission – Seismic assessment of multi-storey buildings

(WCTE) – World Conference on Timber Engineering

(3) Journal Paper Submission with progressive collapse assessment of multi-storey timber buildings

Design and modeling of CLT and CLT-Concrete Floor Diaphragms (Shake-table Testing at UCSD)



NHERI Tall Wood Building Team – Pei et al. *Barbosa, Higgins, Sinha, Rodrigues, DeMeza*

Design and modeling of CLT and CLT-Concrete Floor Diaphragms (Shake-table Testing at UCSD)

Oregon State University

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Design and modeling of CLT and CLT-Concrete Floor Diaphragms (Shake-table Testing at UCSD)

Collaboration

- Design of the diaphragms that comprise two different solutions: CLT panels with surface spline joints and a composite CLT-concrete solution. The diaphragms have to **behave essentially elastic** over 12 ground shaking tests.
- Development of the instrumentation plan to capture measurements used to calibrate the analytical models
- Model the behavior of the mass timber floors through nonlinear models using SAP2000 and OpenSees framework.

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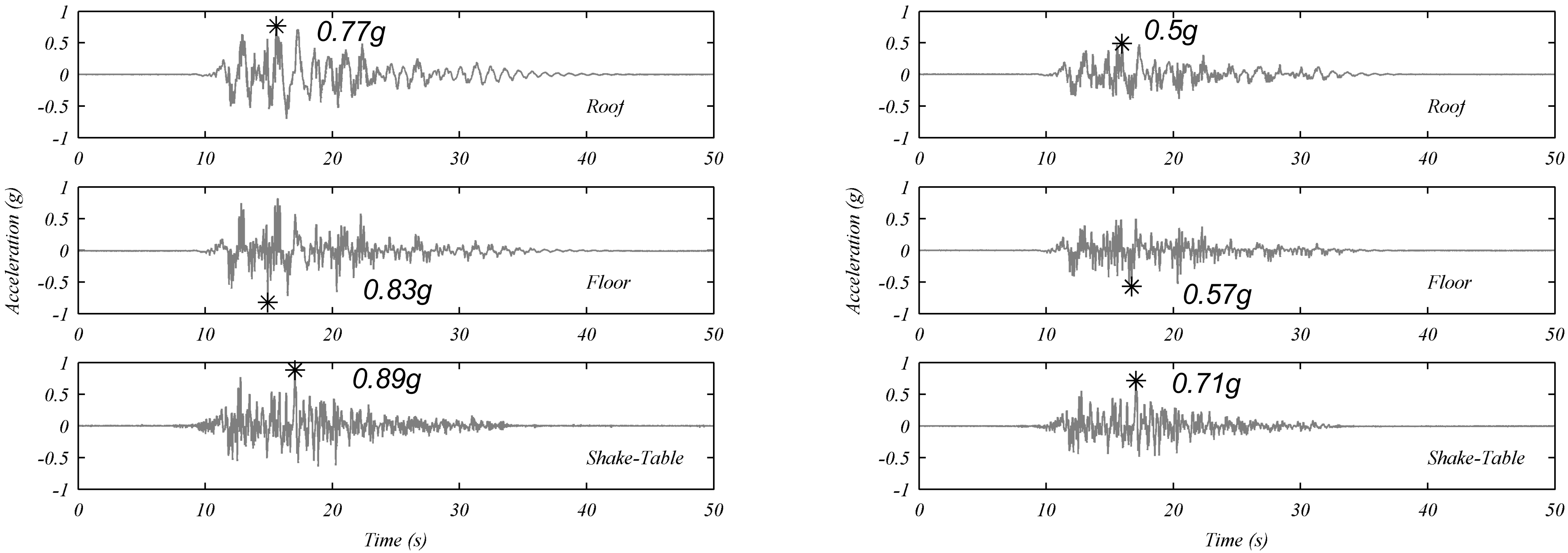
Design and modeling of CLT and CLT-Concrete Floor Diaphragms (Shake-table Testing at UCSD)

Oregon State University

Preliminary Results



(a) Phase 1 – Peak accelerations (b) Phase 2 – Peak accelerations

- 1.2 x MCE => 5% drift, initial yield of rods and minimal crushing of CLT was observed
- Maximum Considered Earthquake defines the peak horizontal accelerations with 2% probability of exceedance in 50 years.

NEHRI Tall Wood Building Team – Pei et al. *Barbosa, Higgins, Sinha, Rodrigues, DeMeza*

THANK YOU!

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