# EXPERIMENTAL TESTS & NUMERICAL MODELING OF CROSS-LAMINATED TIMBER DIAPHRAGMS


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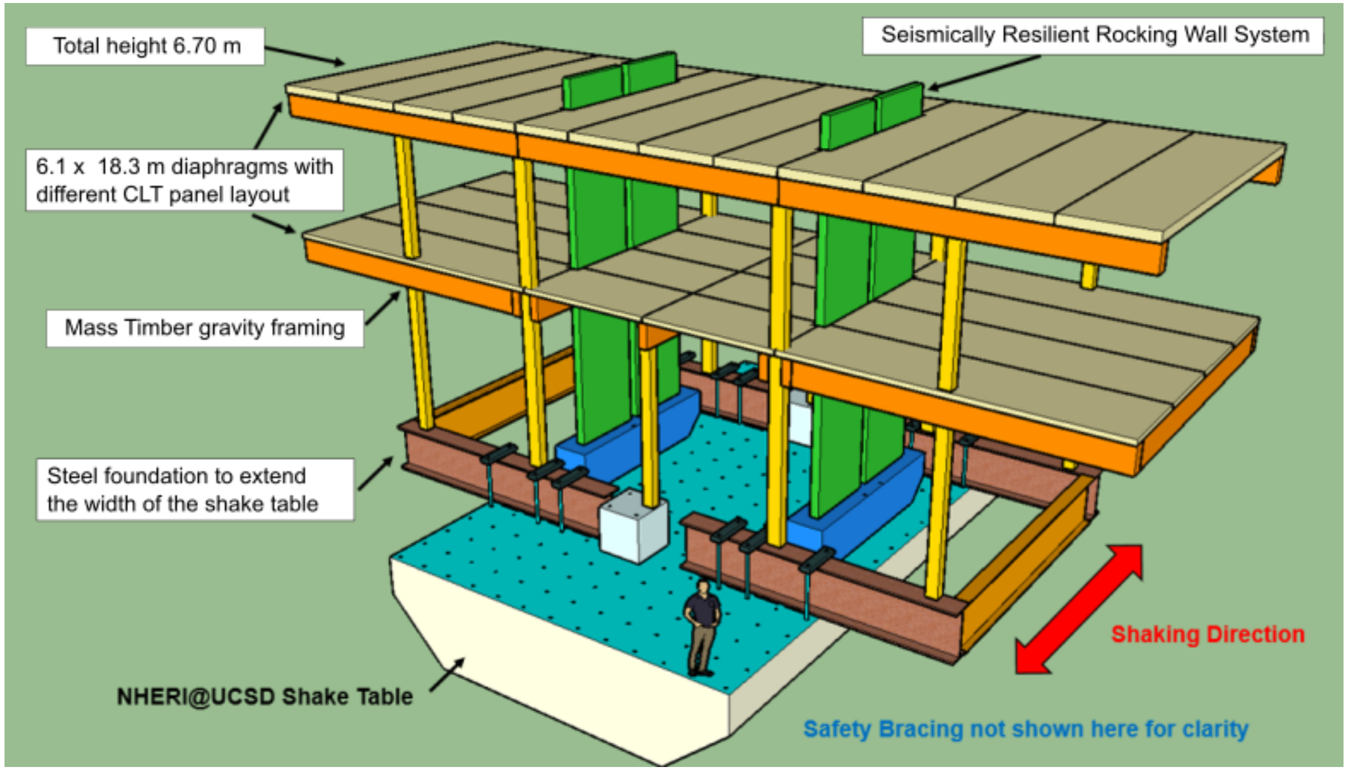
# OUTLINE

- Objectives
- Experimental Setup / Design
- Experimental Results
- Finite Element Modeling
- Experimental vs FEM Correlation
- Conclusions

- Robustness of Multi-Storey Timber Buildings - Ongoing Work

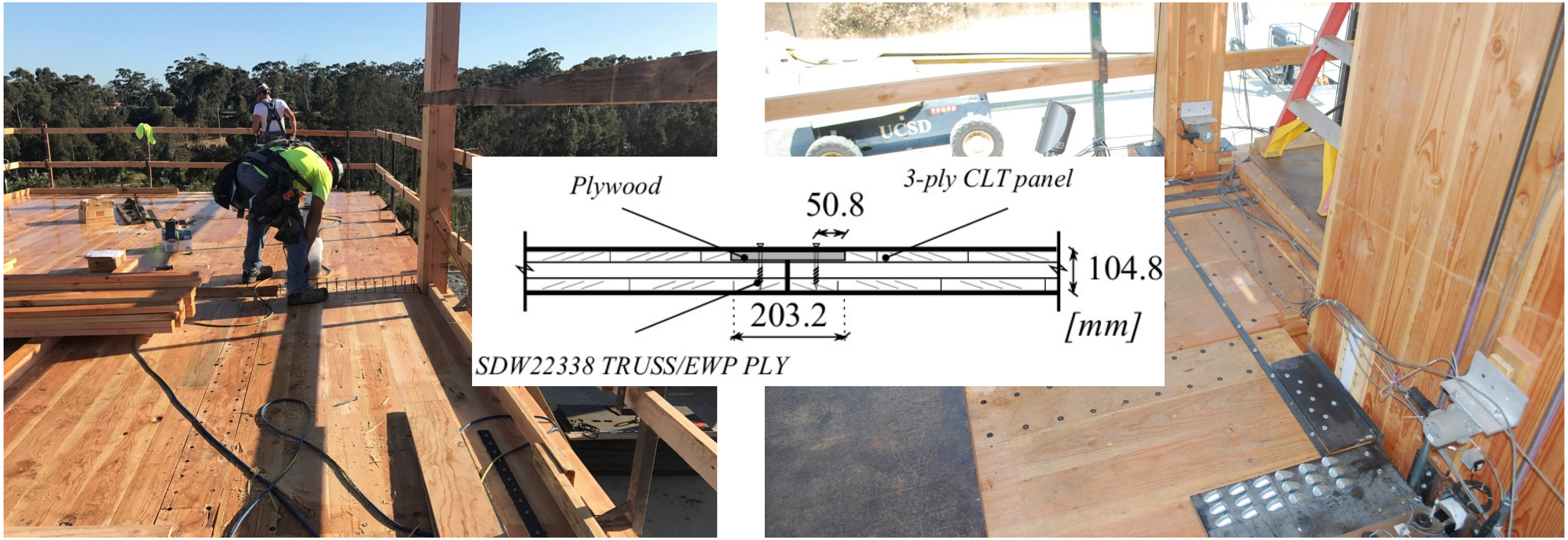
# EXPERIMENTAL SETUP

- Three Wall Systems Tested
  - Post-tensioned self-centering rocking wall designed for Washington
  - Non post-tensioned rocking wall designed for Berkeley
  - CLT shear walls with standard nail shear connectors and rod hold-downs designed for San Francisco



# EXPERIMENTAL SETUP

- Two Diaphragm Designs for all Three Wall Systems
  - Roof – 5-ply CLT Panels + Concrete Topping (Composite slab)
  - **Floor level – 3-ply CLT Panels**



# EXPERIMENTAL SETUP

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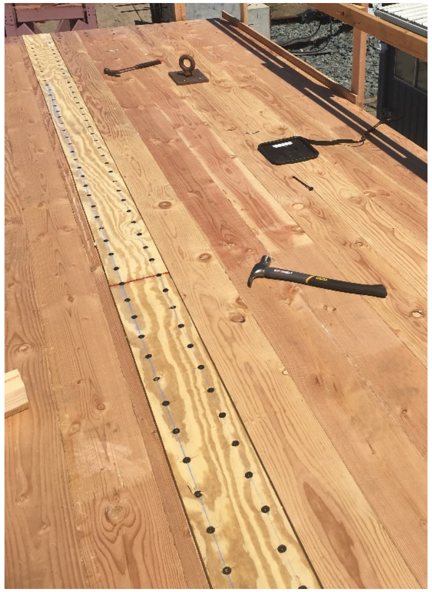
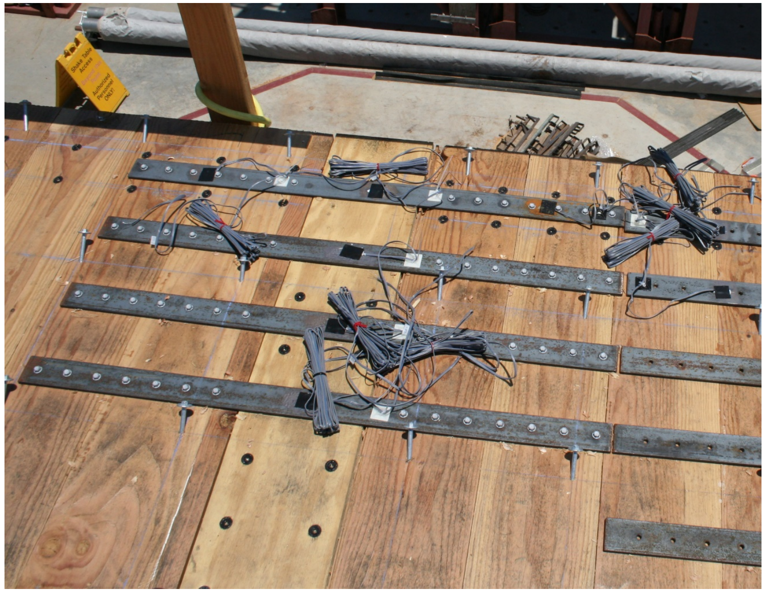
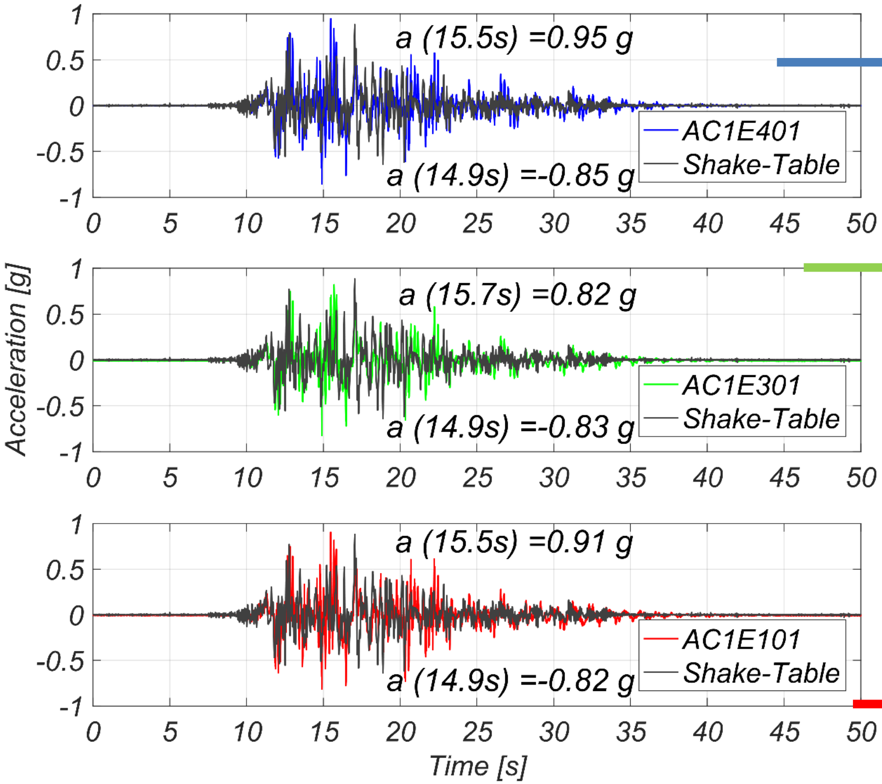


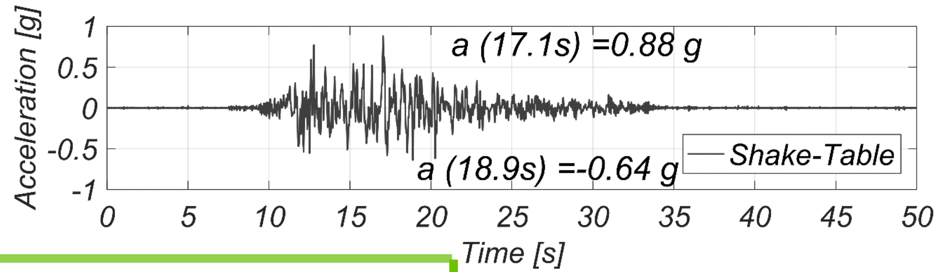


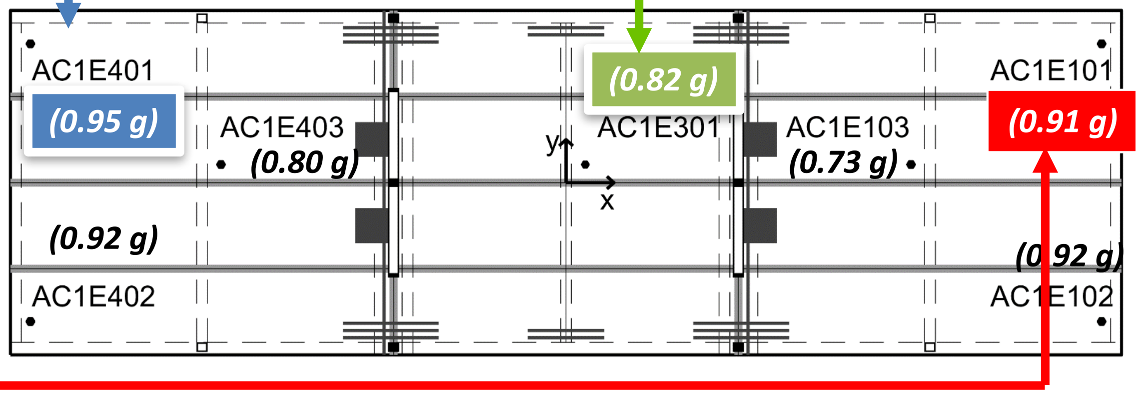
# EXPERIMENTAL RESULTS (FLOOR DIAPHRAGM)

## Average accelerations at diaphragm levels




## Northridge (MCE) – Scale Factor 1.2




## Higher accelerations at the cantilevered ends

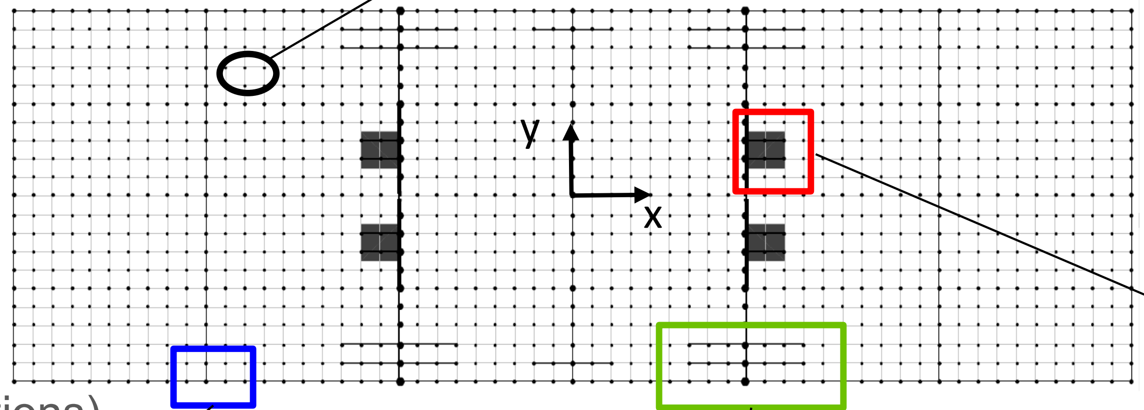
# FINITE ELEMENT MODEL (FLOOR DIAPHRAGM)

**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)

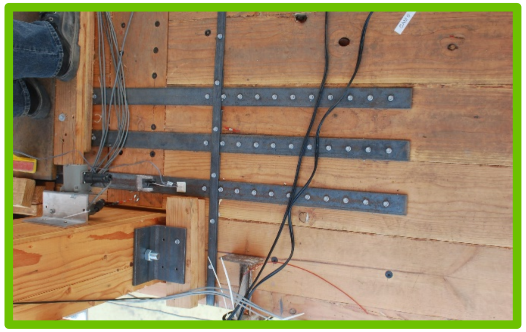



**Zero-length elements (Nonlinear Behavior)**
(CLT-to-Beam Connections)

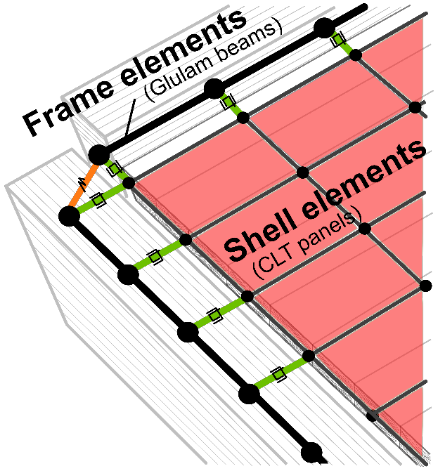
**Mesh Size (304.8 x 304.8 mm)**

**Linear Elastic Frame Elements**
(Beams and Chord splices)

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



# FINITE ELEMENT MODEL (FLOOR DIAPHRAGM)




**Rigid Links (beam-to-beam)**

**Nonlinear Links (CLT-to-beam)**

a)

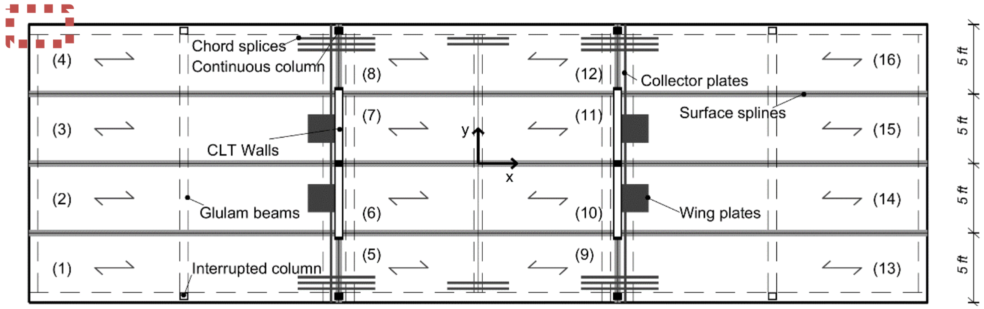
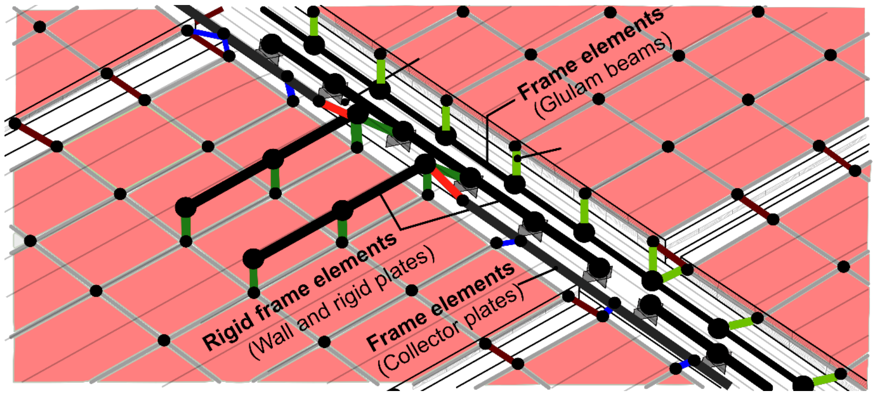
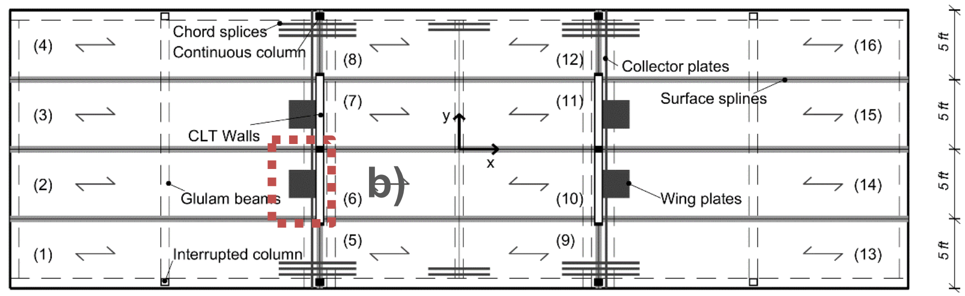



**Figure a)**

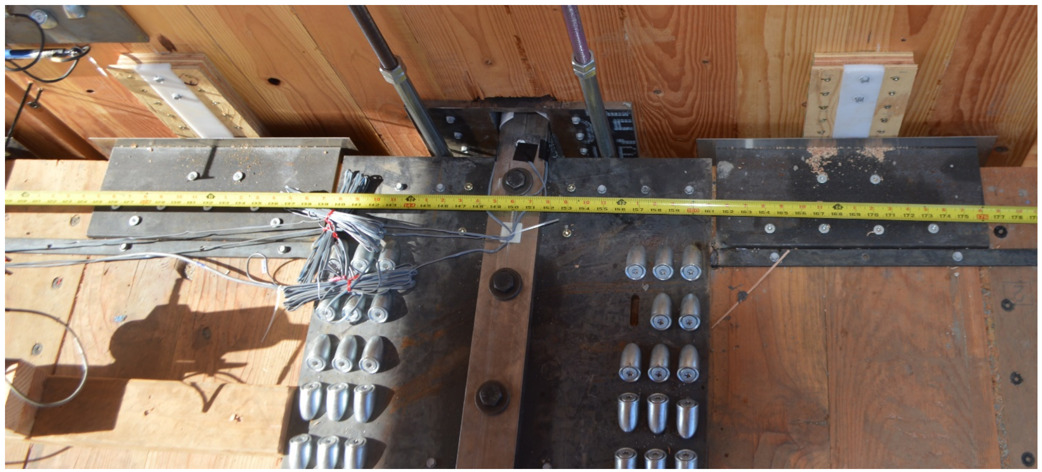
# FINITE ELEMENT MODEL (FLOOR DIAPHRAGM)



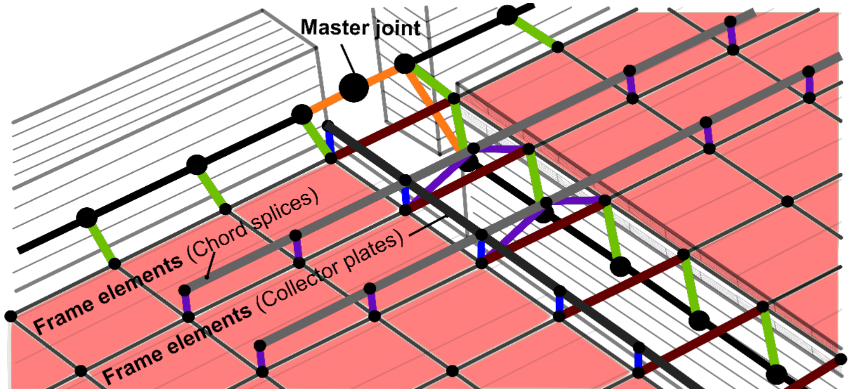




- Rigid Links (CJP Welds)
- Rigid Links (Wing plate-to-CLT)
- Nonlinear Links (Collector-to-CLT)
- Nonlinear Links (CLT-to-beam)
- Nonlinear Links (Surface splines)

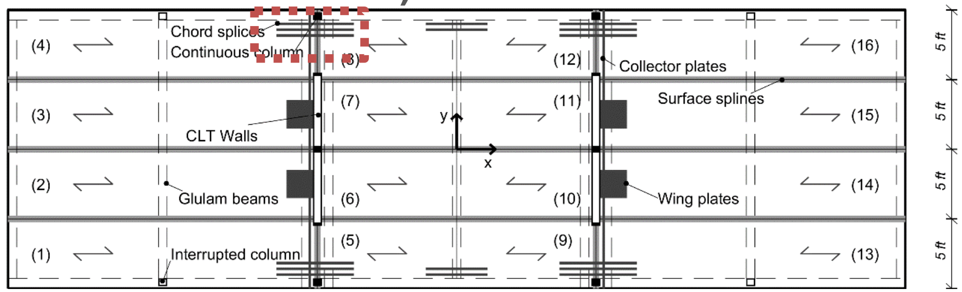
**Figure b)**



# FINITE ELEMENT MODEL (FLOOR DIAPHRAGM)




c)




**Rigid Links (beam-to-beam)**

**Nonlinear Links (Chords-to-CLT)**

**Nonlinear Links (Collector-to-CLT)**

**Nonlinear Links (CLT-to-beam)**

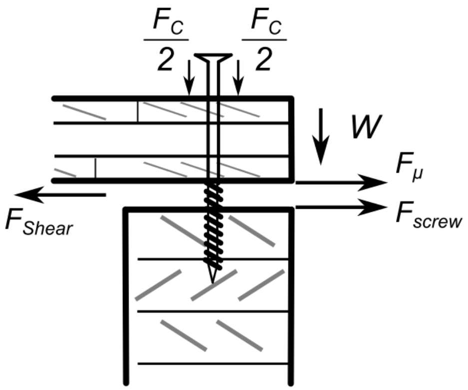
**Nonlinear Links (Surface splines)**

**Figure c)**

# FINITE ELEMENT MODEL (FLOOR DIAPHRAGM)

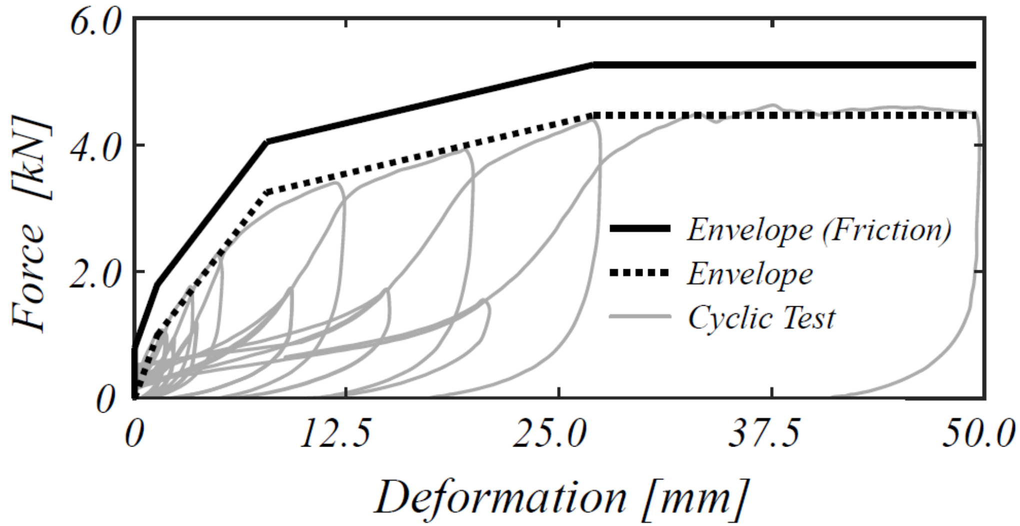
## Friction Force

$$F_{\mu} = (W + F_c) \cdot \mu$$




- Clamping Force ($F_c$) — $F_c = 0.1\ F_y$; $F_c = 0.2\ F_y$
- Weight ($W$)
- Friction coefficient ($\mu$) — $\mu = 0.3$; $\mu = 0.4$; $\mu = 0.5$

## Numerical Model Envelope




Closen, M. (2017). "Performance of clt connections under dynamic loading." Myticon. http://www.my-ti-con.com/resources/slides-clt-connections-dyn-loading-usa.

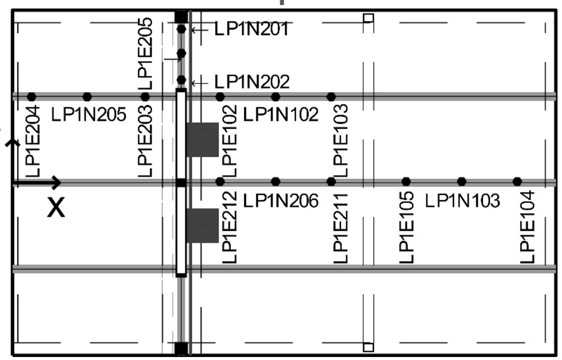
# EXPERIMENTAL vs FEM (FLOOR DIAPHRAGM)

## Nonlinear static analysis

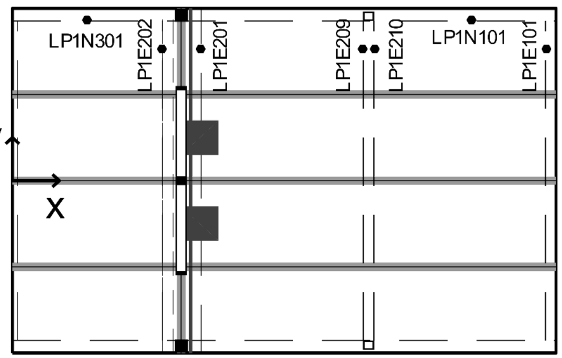
- Nodal Loads Proportional to Nodal Masses
- Maximum Accelerations used to compute Nodal Loads
- Linear Potentiometers measurements used to calibrate the Numerical Model

## Linear Potentiometers

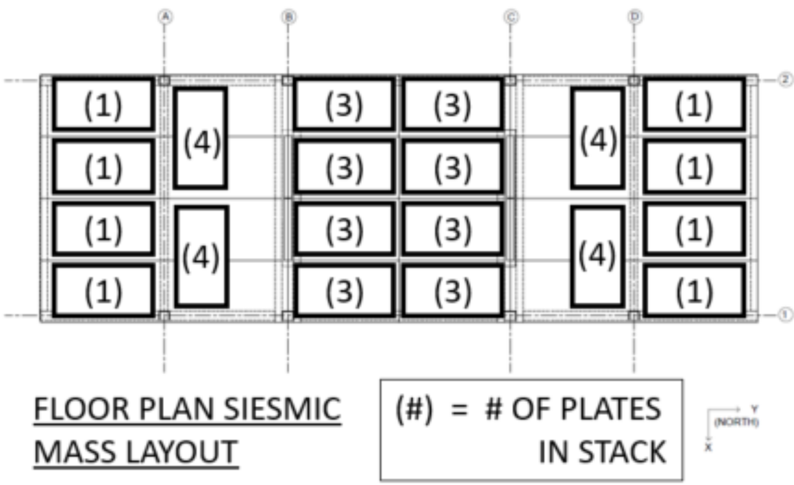
- Surface Splines



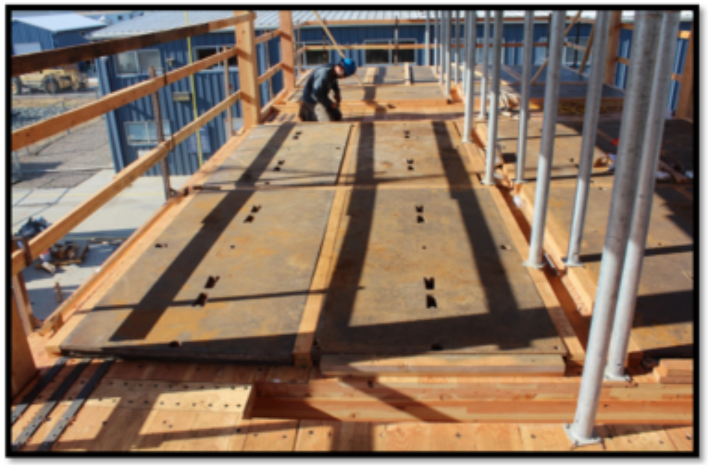

- Panels over beams




## Load Steel plates

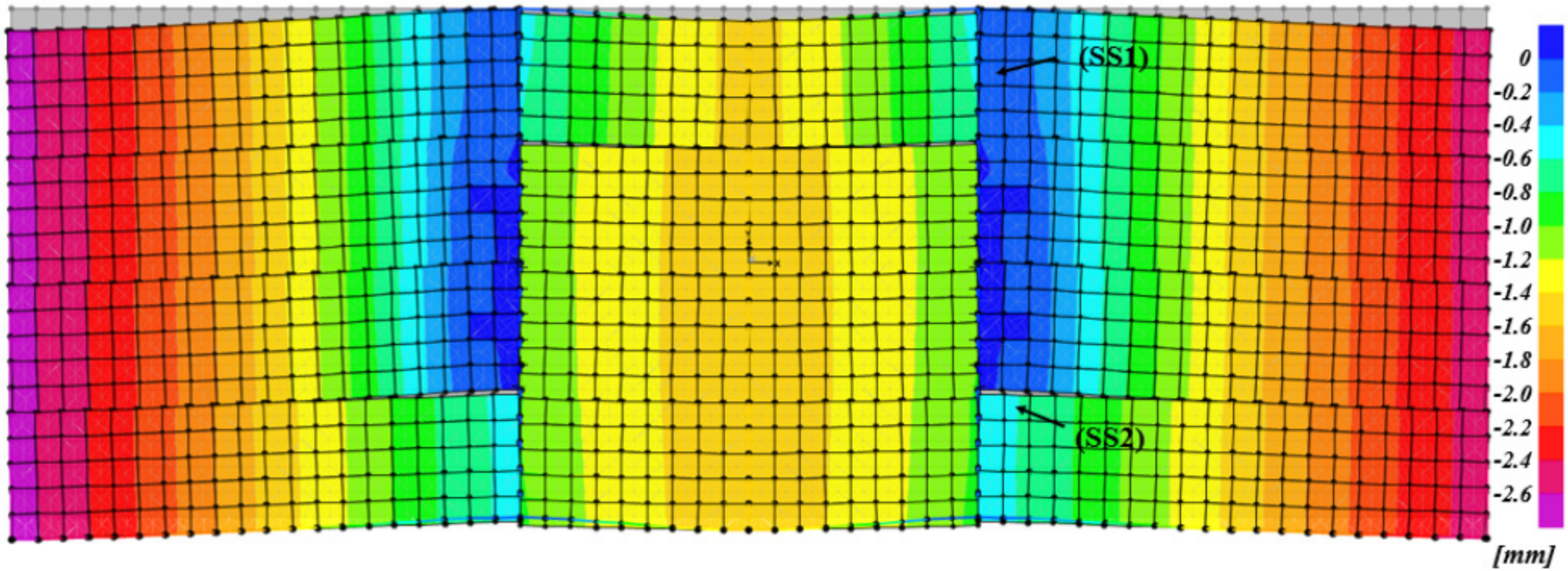


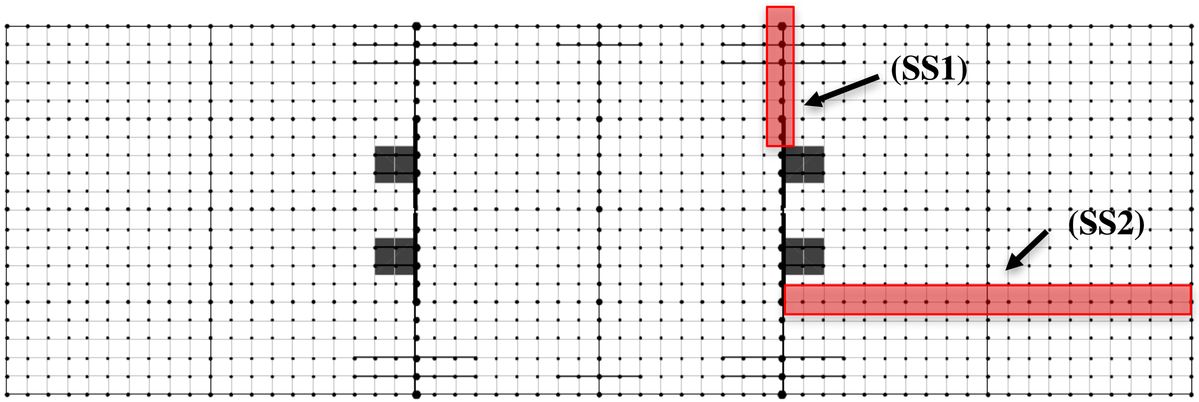

Floor Seismic Mass Plates



# EXPERIMENTAL vs FEM (FLOOR DIAPHRAGM)

**Surface Splines**



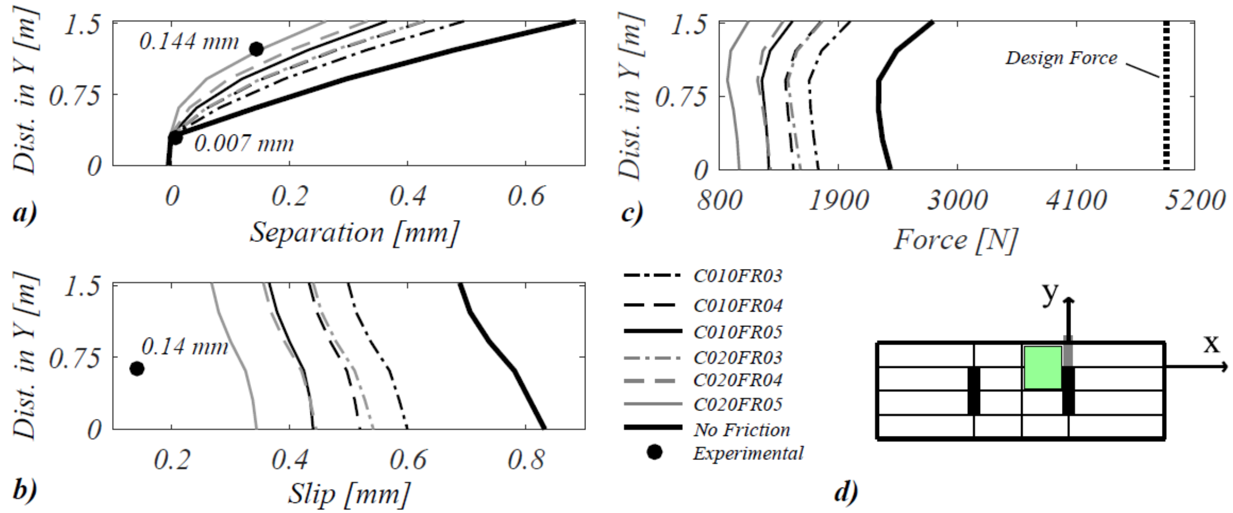



# EXPERIMENTAL vs FEM (FLOOR DIAPHRAGM)

**Surface Splines**

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

## Numerical results of surface spline SS1




Clamping Force

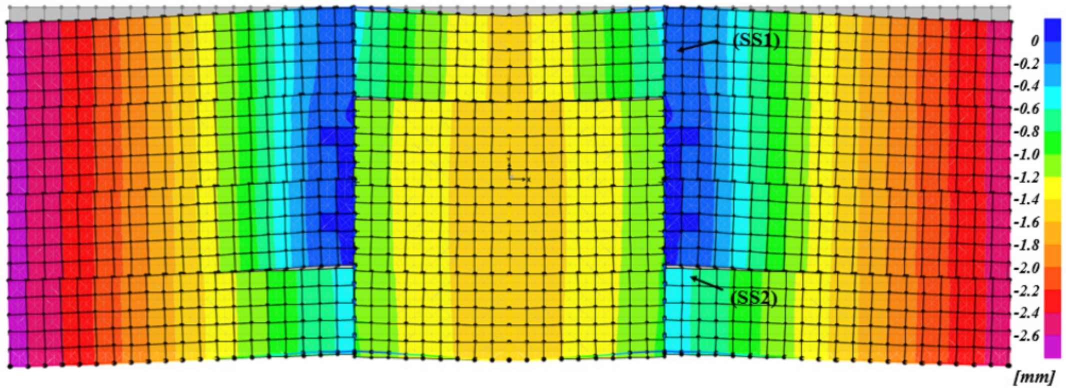
Friction Coefficient

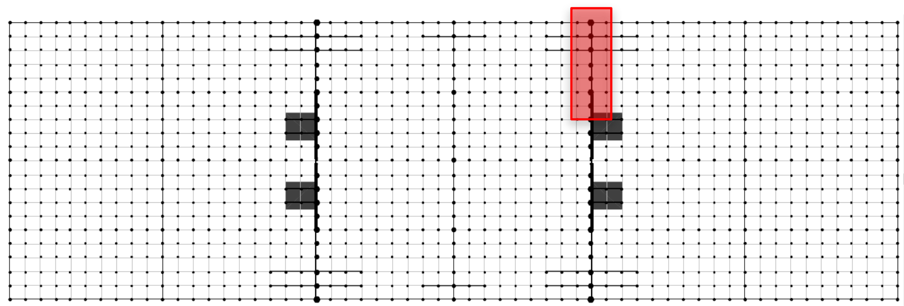
**C010FR04:**

$F_c = 0.1\ F_y$ to $0.2\ F_y$

$\mu = 0.3$ to $0.5$

- The model captures the maximum response, when friction is considered on the numerical model.
- A conservative design is obtained if friction is neglected



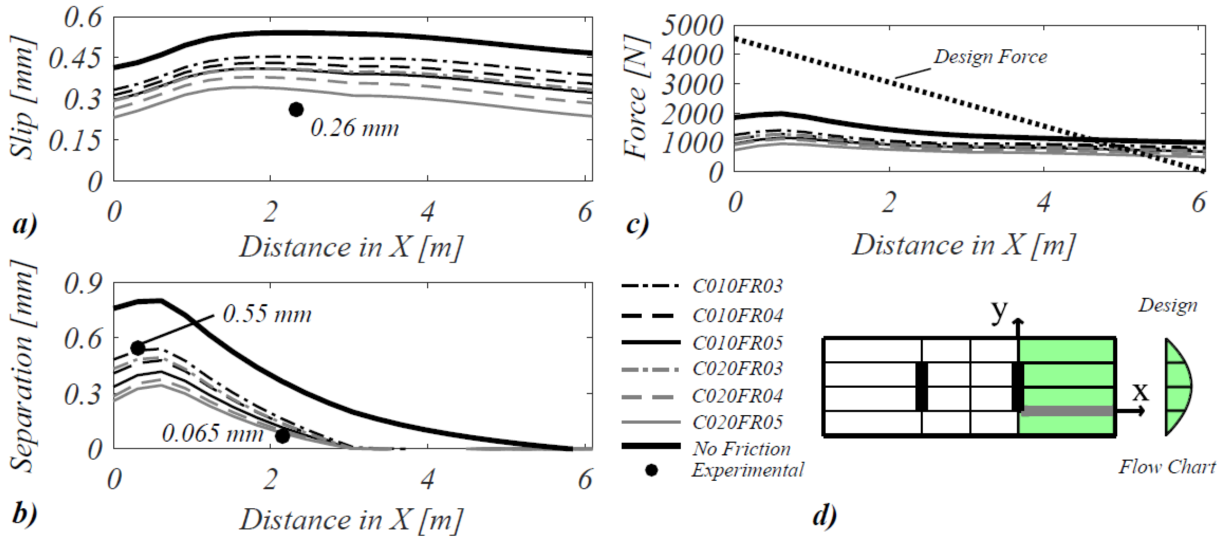



# EXPERIMENTAL vs FEM (FLOOR DIAPHRAGM)

**Surface Splines**

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

## Numerical results of surface spline SS2




Clamping Force

Friction Coefficient

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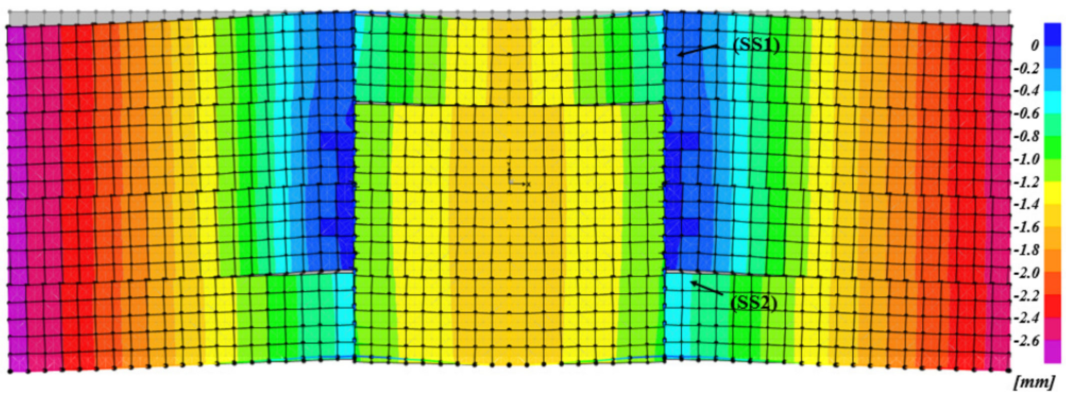
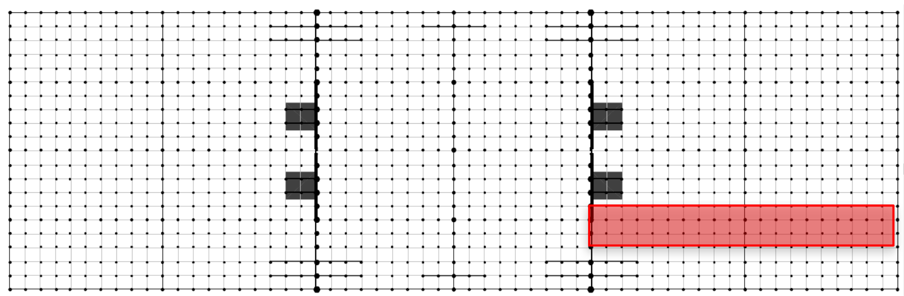


# CONCLUSIONS

- 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.

- CLT diaphragms were designed in accordance with principles of mechanics using values of fastener and member strength in accordance with latest test results available in the literature and NDS.

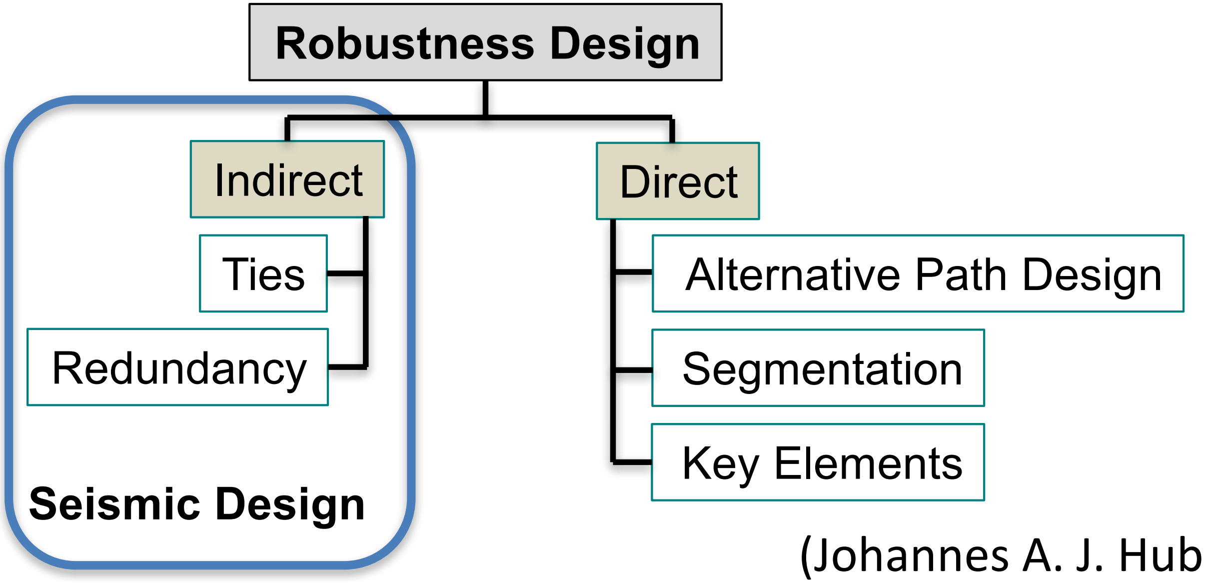
- Modeling of friction is crucial to capture the surface spline deformations at all levels of excitation.

- 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.

- The chord forces estimated based on measured strains were ½ of the forces used in the design.

- The FE modeling approach captures the contribution of splices and chords for stiffness and force distribution. Therefore chord forces estimated by the model are lower than those calculated in the design performed.

# Robustness of multi-storey timber buildings in seismic regions

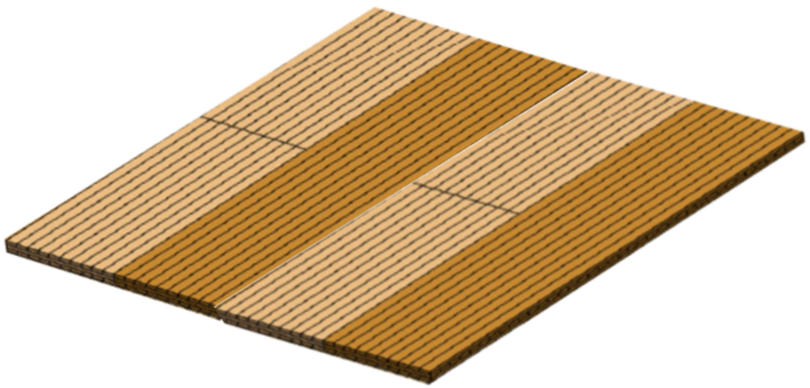



(Johannes A. J. Huber et al. 2018)

- **Floors in post and beam constructions** may make possible membrane action above removed elements.
- Robust timber posts and beams should include a redundant bracing system, **which could be achieved by moment-resisting connections**, by shear walls or by stair and lift cores.
- When the **behavior of connections is understood**, design guidelines for robust construction of post and beams structures should be created.
- The **nonlinear static, the nonlinear dynamic and the pushover procedures** for alternative load path analysis do not seem to be as established for timber buildings as for concrete and steel.

# Robustness of multi-storey timber buildings in seismic regions

- **CLT diaphragm**



### Static Analysis

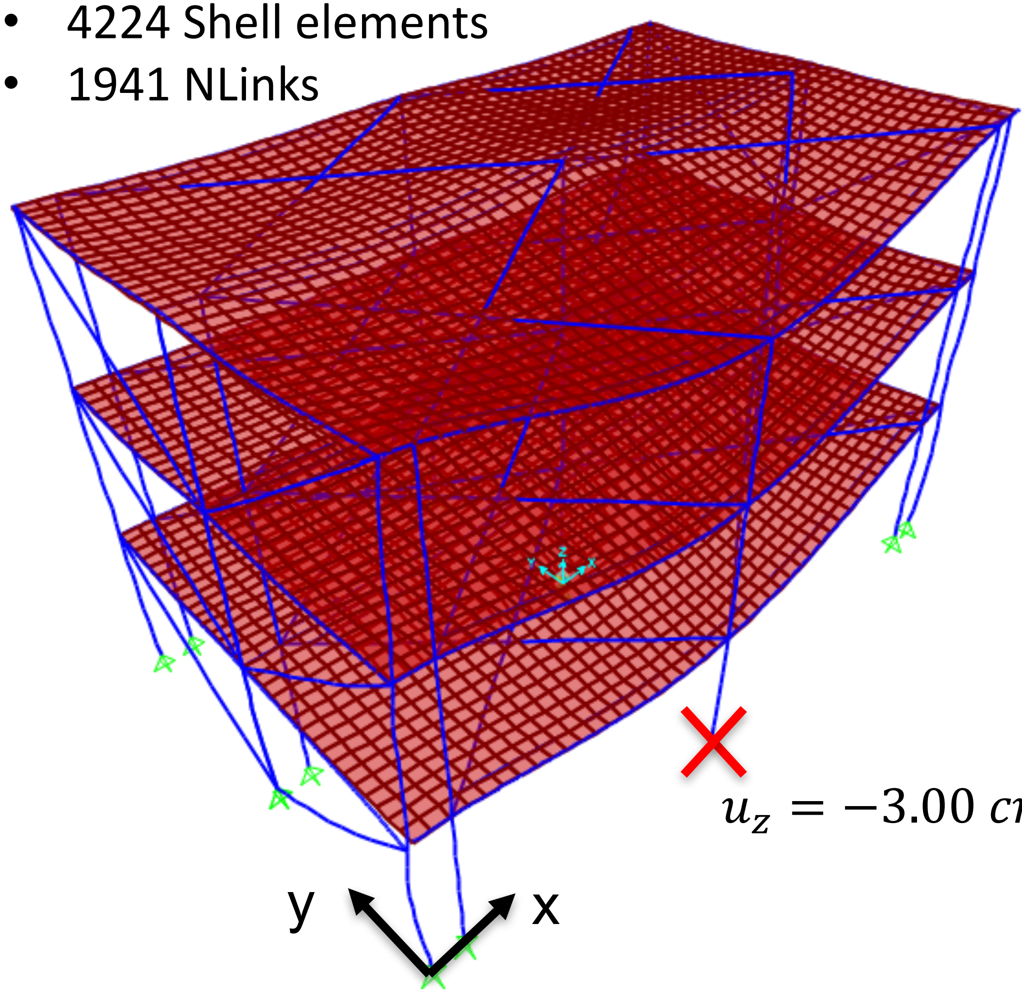
**Non-linear**

- dynamic effects via DLF
- includes geometric non-linearities
- includes plasticity
- moderate complexity
- realistic results

Dynamic Load Factor (DLF = 1.5)

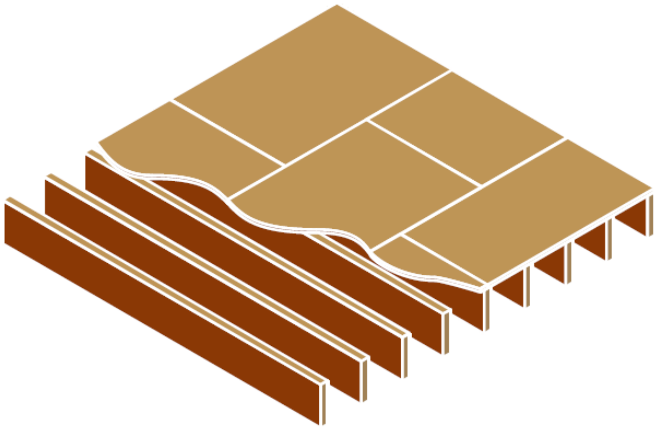
**Alternative Load Path Analysis**

- 6269 Nodes
- 1035 Frame elements
- 4224 Shell elements
- 1941 NLinks



# Robustness of multi-storey timber buildings in seismic regions

- **Unblocked diaphragm**



**Static Analysis**

**Non-linear**

- dynamic effects via DLF
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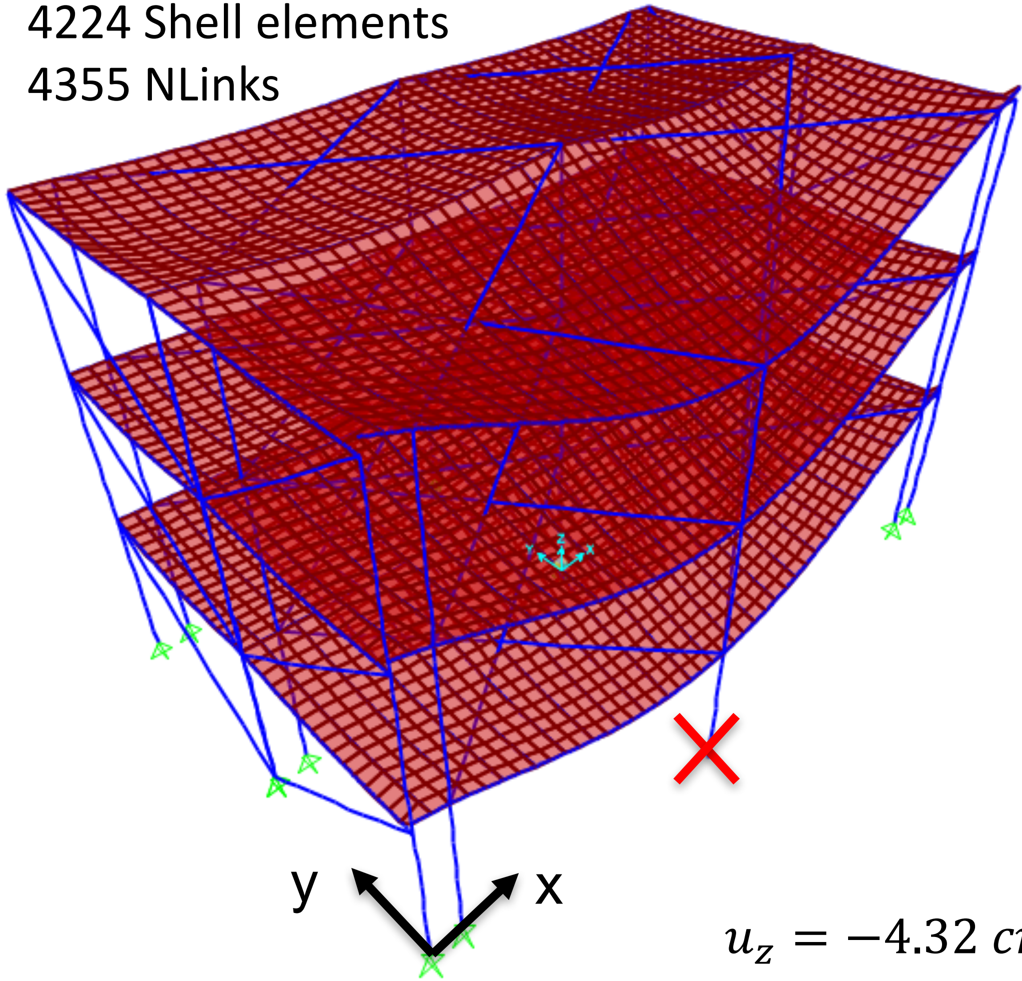
- moderate complexity
- realistic results

Dynamic Load Factor (DLF = 1.5)

**Alternative Load Path Analysis**

- 8874 Nodes
- 2787 Frame elements
- 4224 Shell elements
- 4355 NLinks




$u_z = -4.32\ cm$

# Robustness of multi-storey timber buildings in seismic regions

**Task 1** Introduction

*Tools for robustness assessment*

**Task 2** Framework for Robustness assessment

**Task 3** Progressive collapse assessment

**Task 4** Seismic Assessment

*Implementation of the framework*

**Task 5** Robustness assessment of multi-storey timber buildings

Proposal of guidelines for robustness design of multi-storey timber buildings

**Task 6** Writing of thesis, reports and papers
Dissemination of the results

### Static Analysis

**Non-linear**

- dynamic effects via DLF
- includes geometric non-linearities
- includes plasticity
- moderate complexity
- realistic results

- DLF ∈ [1.0,2.0]

**OpenSees**

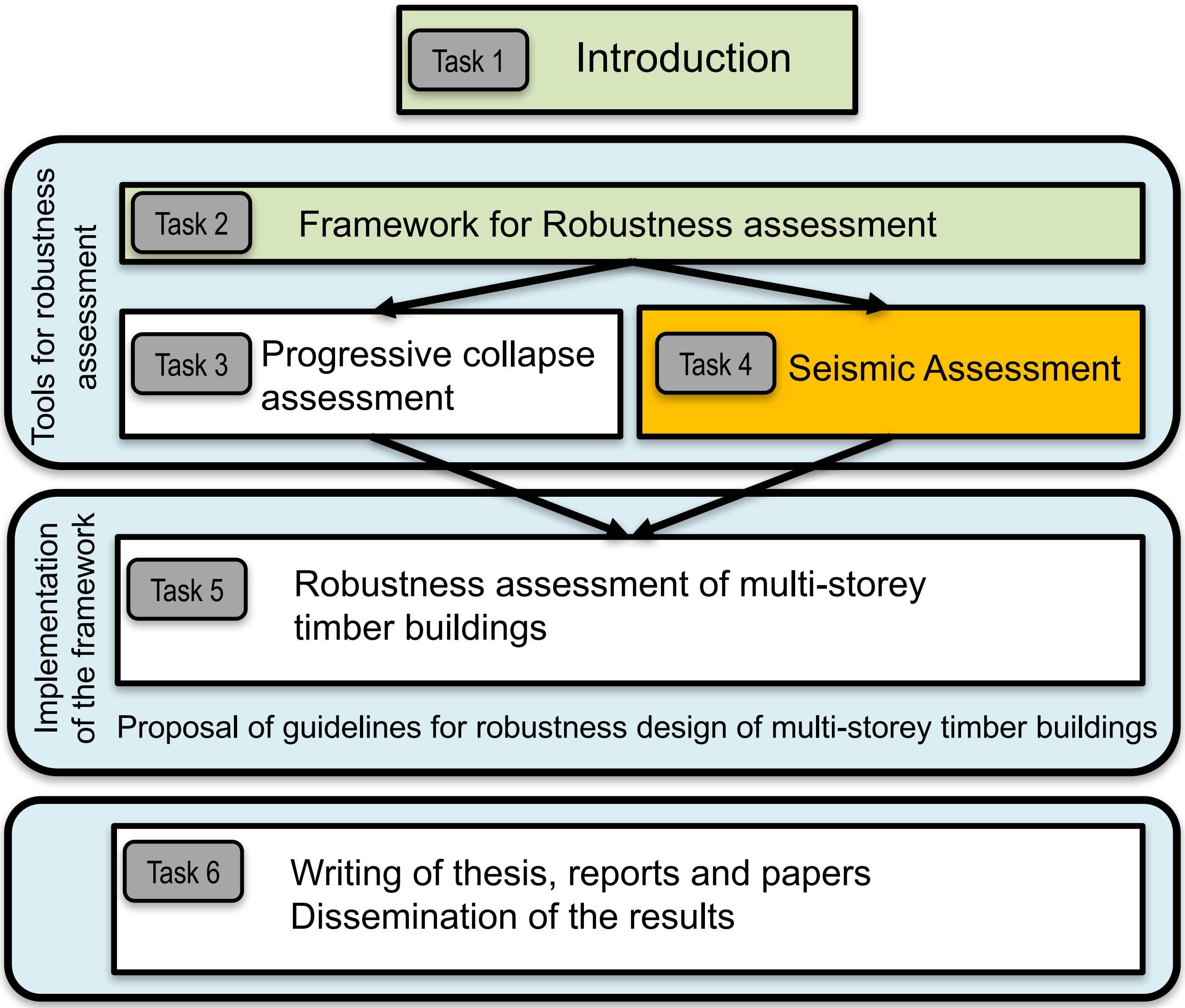
- Elements Removal

**Uncertainties**

- Timber properties
- Connections
- Loads
- Dynamic Load Factor

$$P(C) = \underbrace{\underbrace{P(C|D)}_{\text{Robustness}} \cdot \underbrace{P(D|E)}_{\text{Vulnerability}} \cdot \underbrace{P(E)}_{\text{Exposure}}}_{\text{CollapseResistance}}$$

# Robustness of multi-storey timber buildings in seismic regions




- **Incremental Dynamic Analysis**

  **OpenSees**

  - Nonlinear Dynamic Analysis

  **Uncertainties**

  - Timber properties
  - Connections
  - Loads

- **Fragility Functions**

  (Rodrigues et al. 2017)

THANK YOU!