NHERI Lehigh – UCSD –SimCenter Collaboration Workshop
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MULTI-DIRECTIONAL CYCLIC TESTING OF CROSS-LAMINATED TIMBER ROCKING WALL-FLOOR DIAPHRAGM SUB-ASSEMBLIES

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REAL-TIME MULTI-DIRECTIONAL SIMULATION
NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE
NSF
DESIGNSAFE-CI
A NATURAL HAZARDS ENGINEERING COMMUNITY

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Acknowledgments

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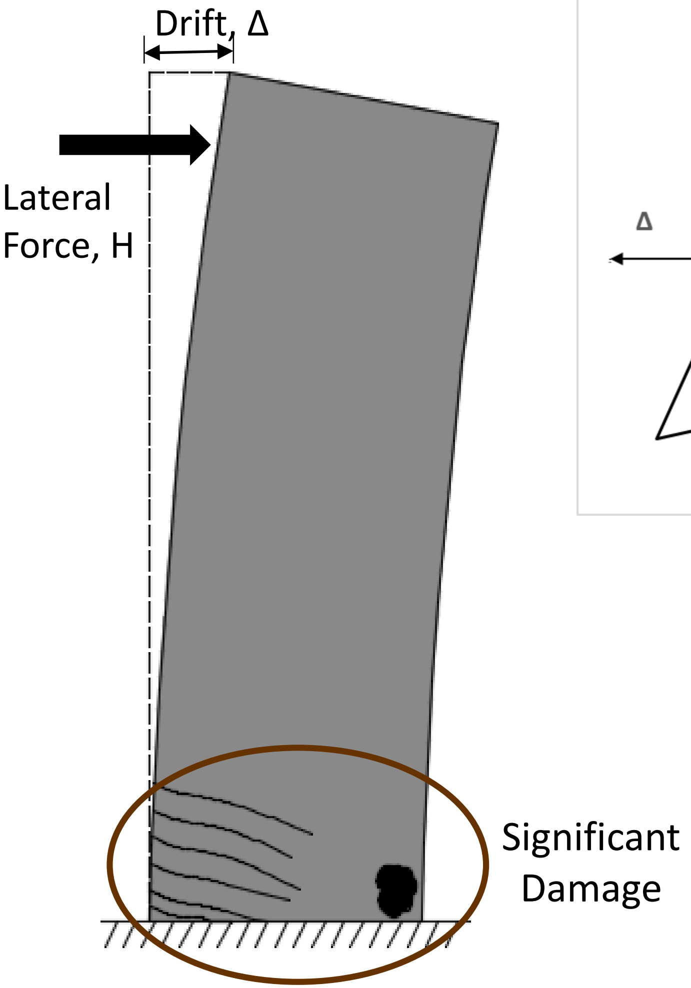
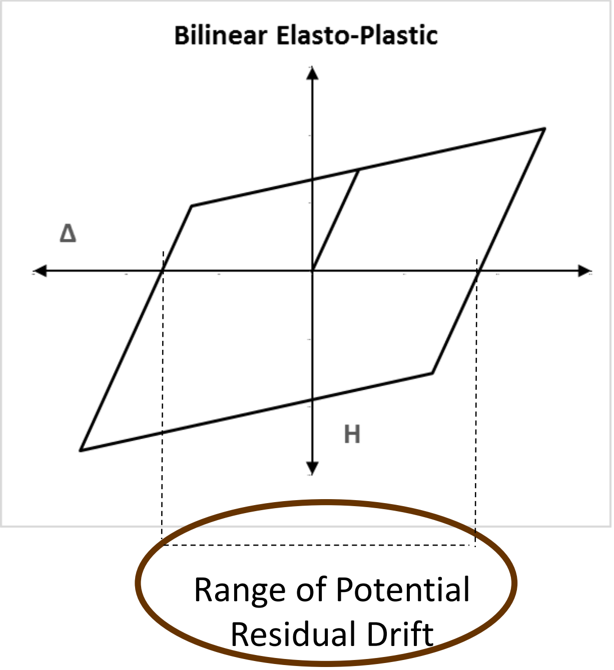
Outline

- **Introduction**
- Experimental Program
- Test Subassembly 3D Control Algorithm
- Preliminary Results
- Summary and Conclusions

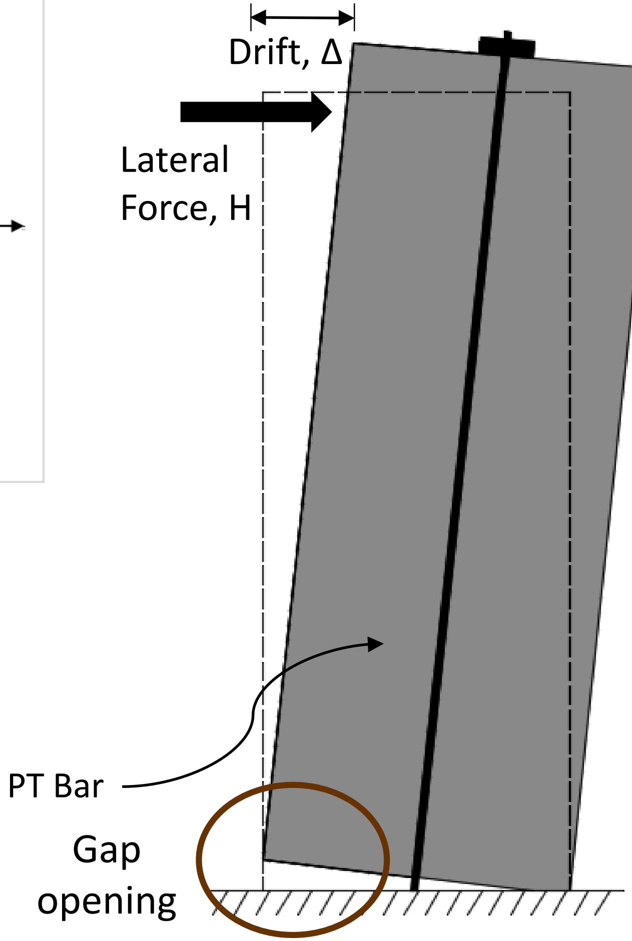
Introduction

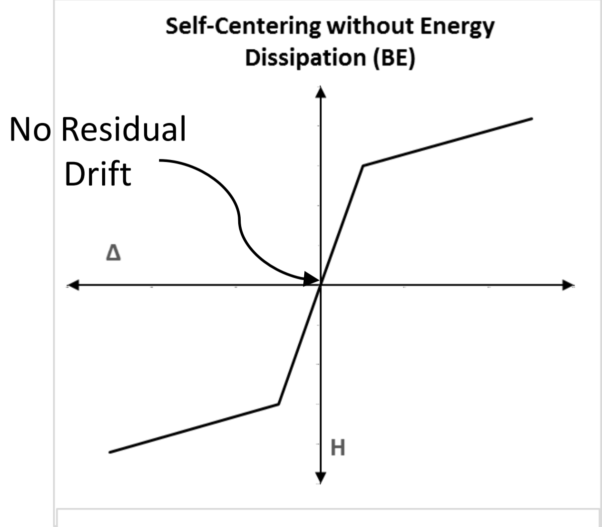
- **Conventional Shear Wall Lateral Force Systems**

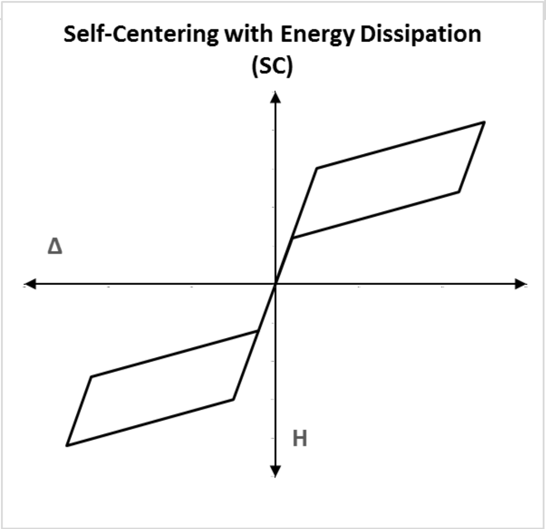




- **Self-Centering Shear Wall Lateral Force Systems**

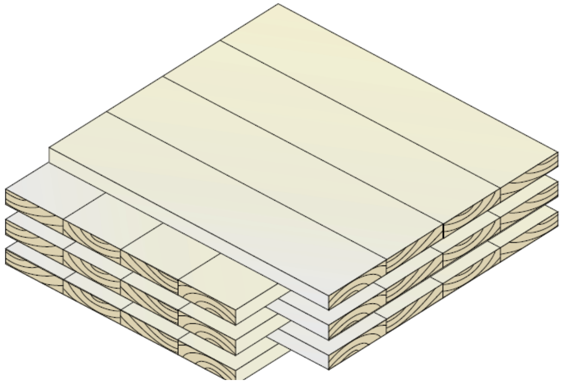






Cross-Laminated Timber Shear Wall

- Cross-laminated timber (CLT) is an engineered wood structural component fabricated by laminating layers of timber boards in an orthogonal pattern and glued together on their wide face
- This panelized product utilizes smaller size lumber to create solid wood panels that be used as wall and floor components
- CLT construction is gaining traction among building owners and investors and becoming a viable option for tall wood buildings



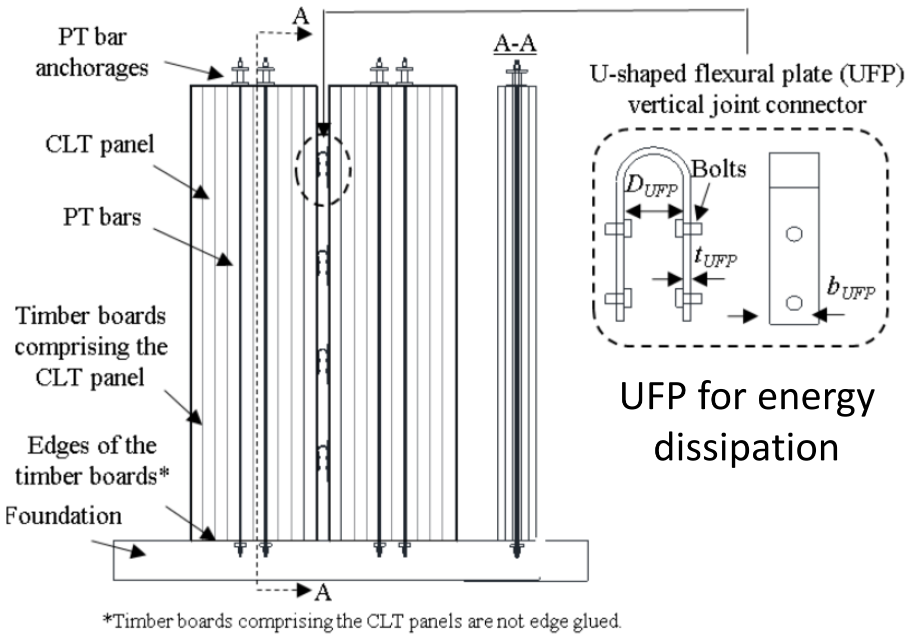
CLT Panel [1]

CLT 10 stories building in Brisbane, Australia

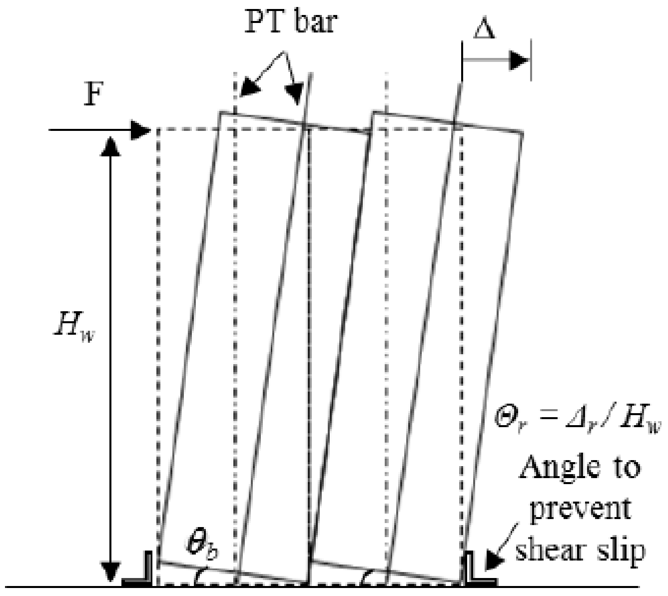
[1] CLT Handbook (2013): Cross-Laminated Timber- US Edition, FPInnovation

Self-Centering Cross-Laminated Timber Shear Wall

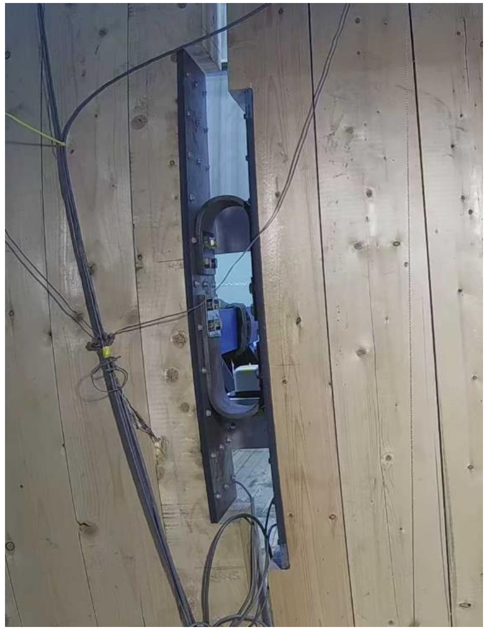
- Seismically resilient structural wood buildings using Self-Centering (SC) rocking post-tensioned CLT structural walls (SC-CLT walls)



Test Specimen for SC-CLT Coupled wall [2]



Displaced Configuration [2]



UFP behavior under rocking state

[2] Akbas, T. (2016). "Seismic Response Analysis of Structures with Nonlinear Mechanisms Using a Modal Approach," Ph.D. Thesis, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, USA.

Knowledge Gaps

- Lack of knowledge of behavior of SC-CLT rocking walls and other building components under **<u>bidirectional loading</u>**
- Lack of knowledge on seismically **<u>resilient</u>** wood structural systems for tall buildings
- Lack of a seismic design methodology to achieve resilience considering the **<u>entire building system, including non-structural systems</u>**

Christchurch, New Zealand 2011: Approximately 50% of the buildings in the central business district were declared unusable [3]

[3] Field Manual: Postearthquake Safety Evaluation of Buildings; Applied Technology Council (ATC): Redwood City, CA, USA, 2005.

Overview

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- **Experimental Program**
- Test Subassembly 3D Control Algorithm
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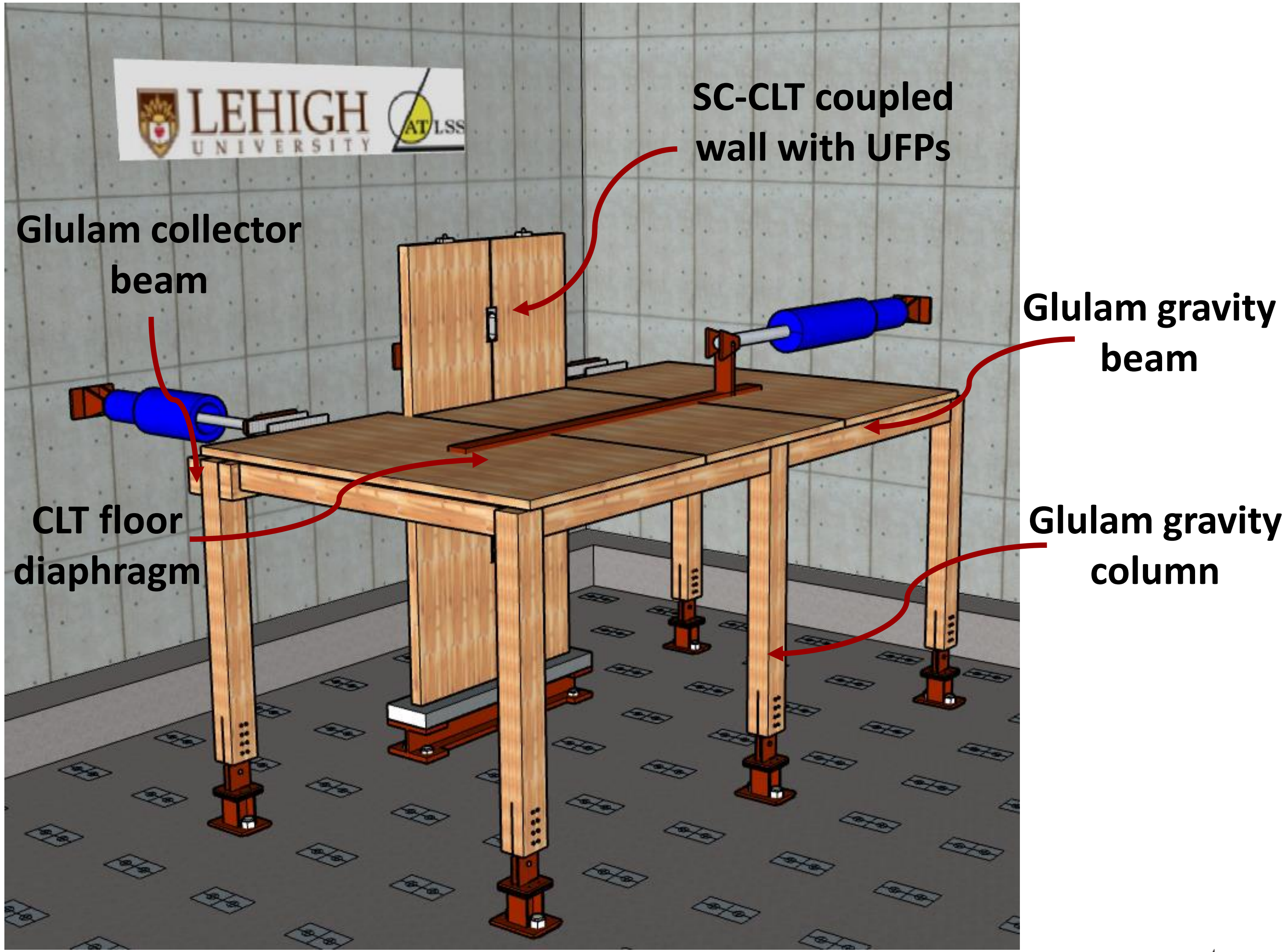
Experimental Program

<u>3D CLT-Floor Diaphragm Subassembly</u>

- 0.625-Scale
- Lateral force resisting system; PT SC-CLT coupled wall
- CLT floor diaphragm
- Glulam collector beams
- Gravity load system; glulam gravity columns and beams
- **Unidirectional** and **bidirectional** loading



Test Setup and Specimen

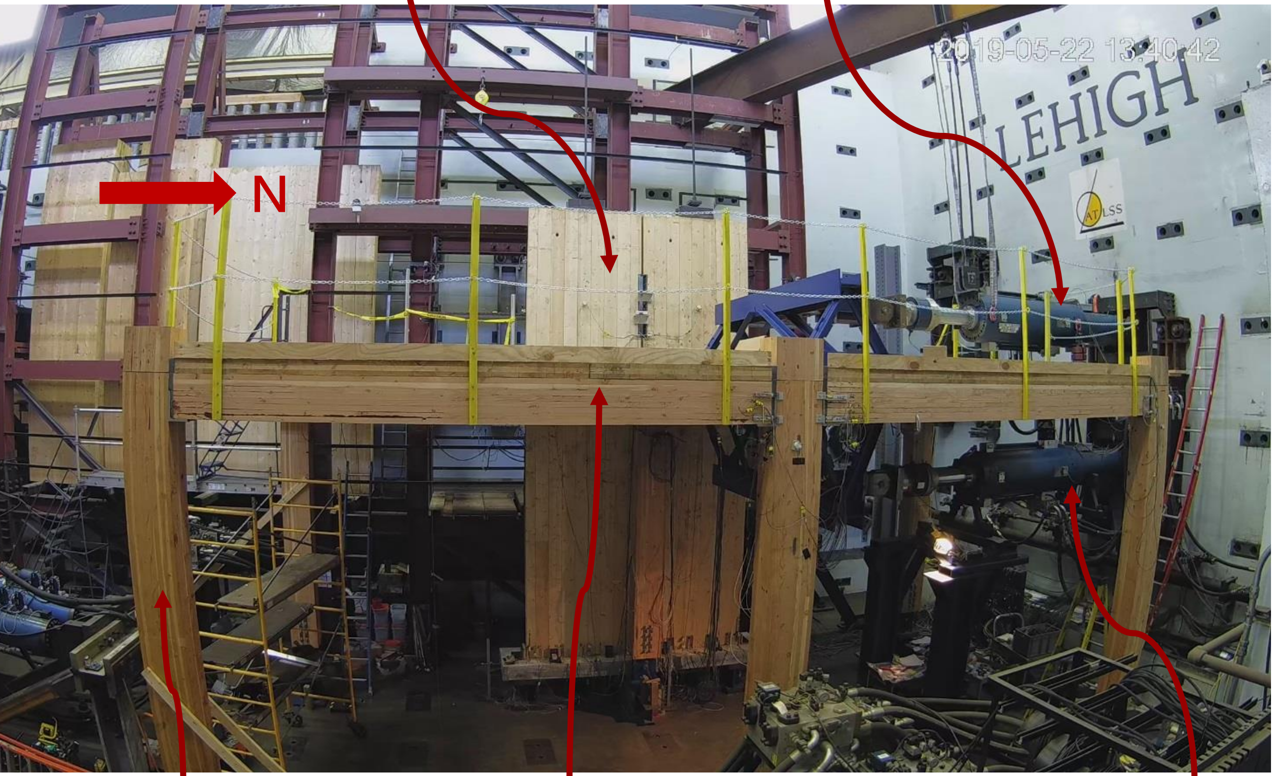
SC-CLT Coupled Wall with UFPs

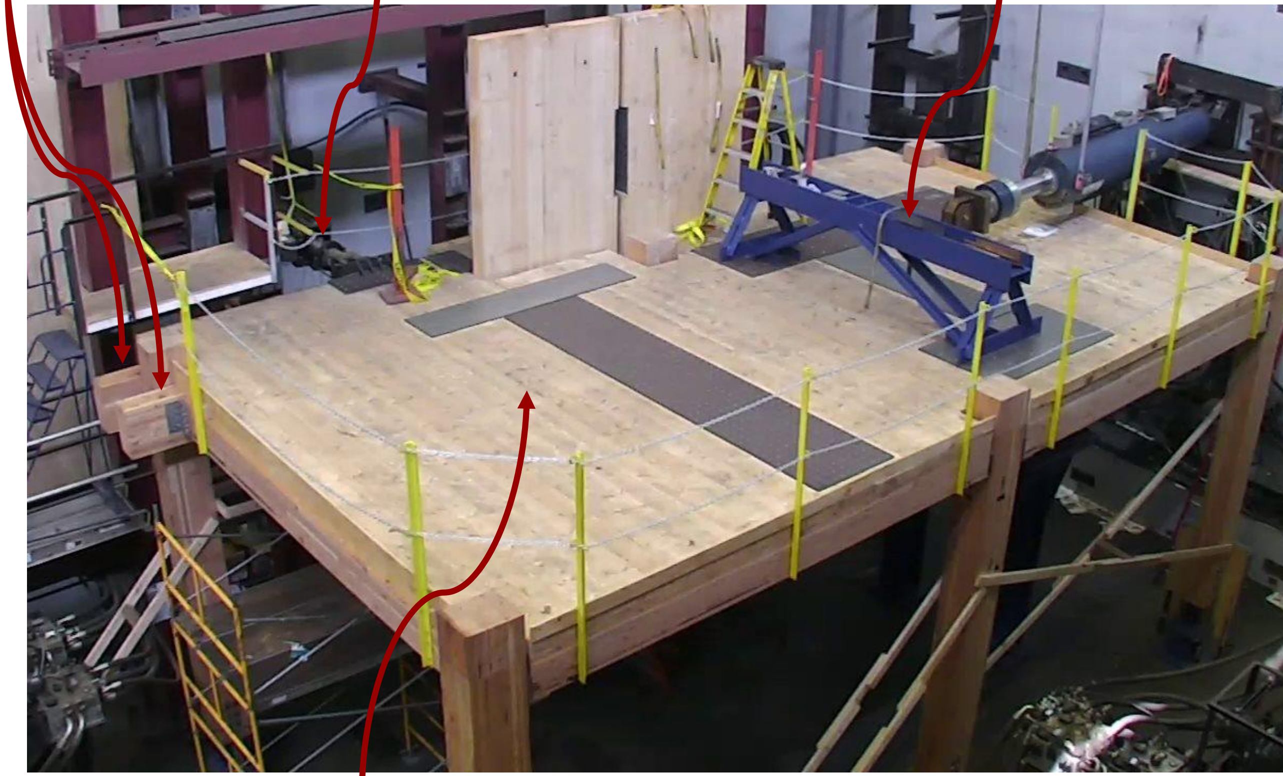
Top In-plane Actuator, A_1

Glulam Collector Beams

South Out-of-plane Actuator, A_4

Transverse Loading Beam





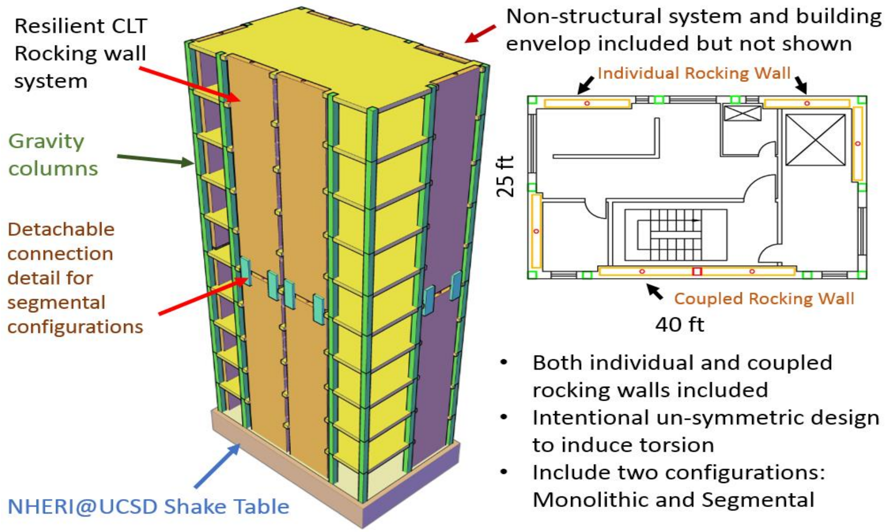
Glulam Gravity Column

Glulam Gravity Beam

Bottom In-plane Actuator, A_2

CLT Floor Diaphragm

Test Matrix

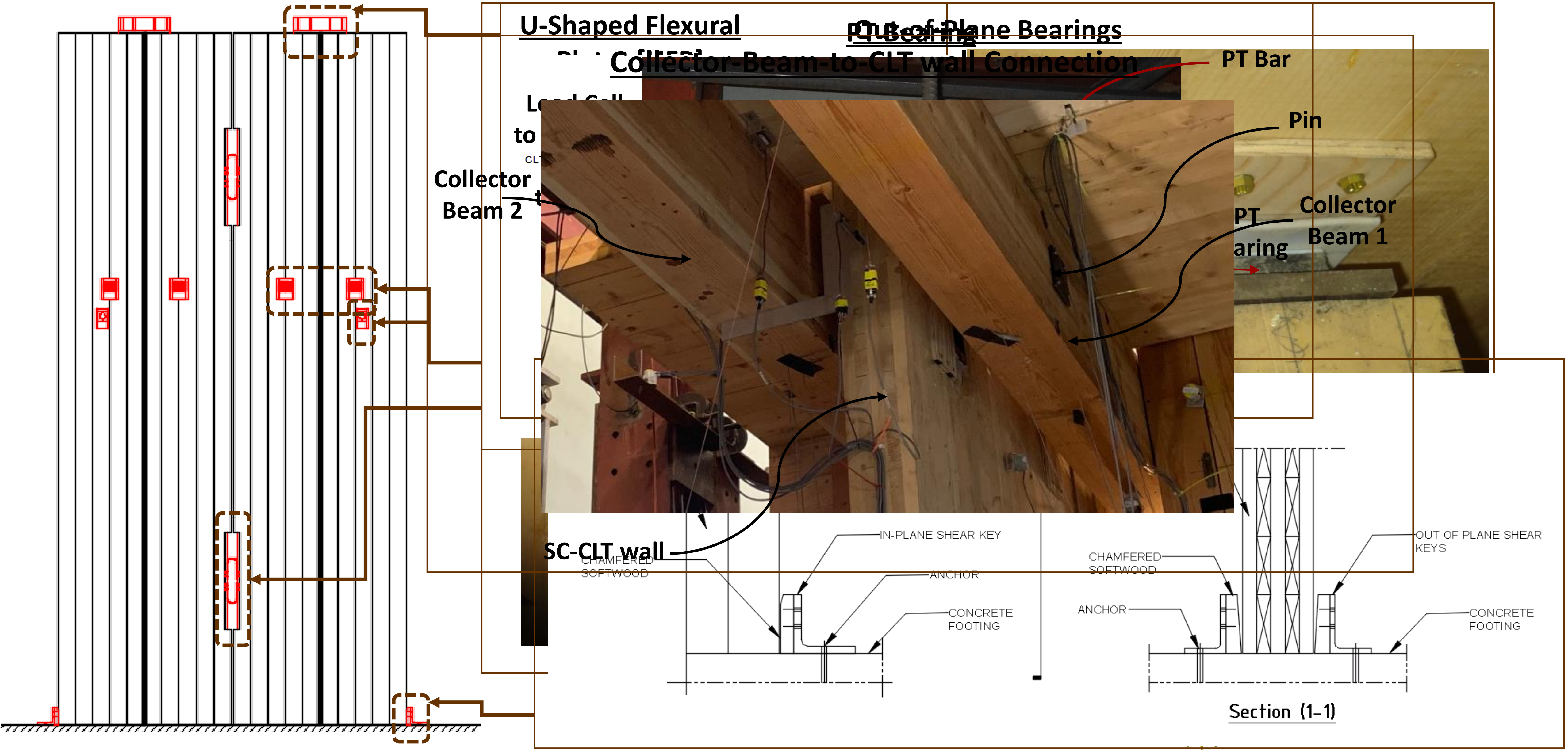


- Both individual and coupled rocking walls included
- Intentional un-symmetric design to induce torsion
- Include two configurations: Monolithic and Segmental

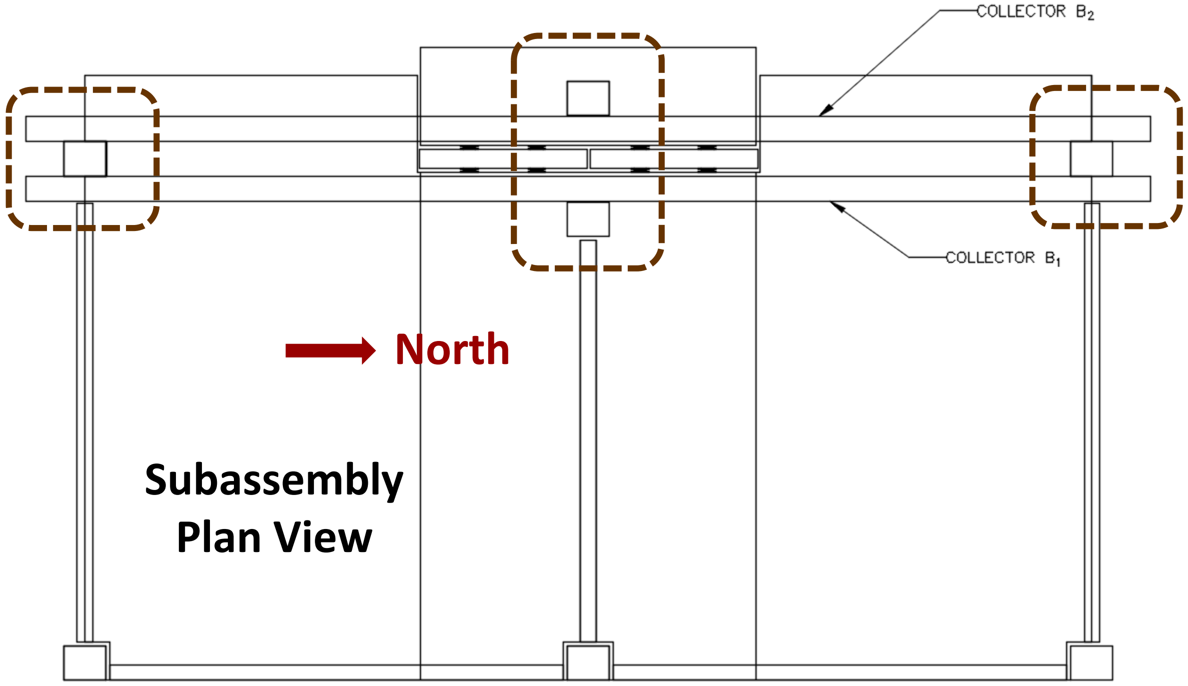
➢ **Results of test specimen components are used for design of 10-Story CLT building shake table test specimen at University of California San Diego (UCSD)**

S: Structural (Lehigh), NS: Non-Structural (UNR, Lehigh subassembly)

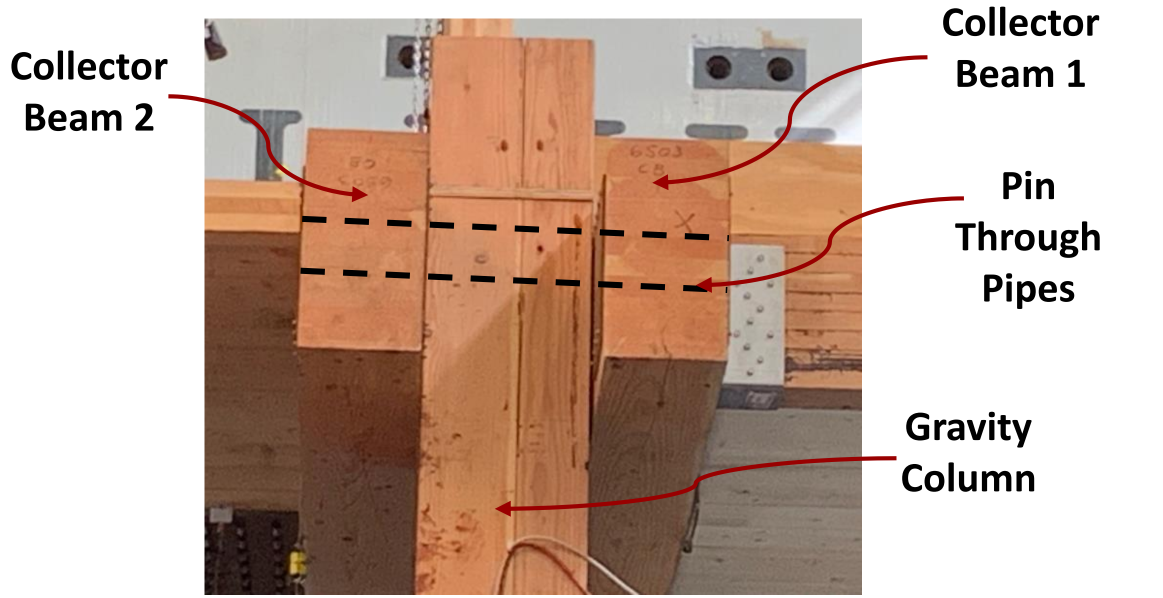
SC-CLT Wall Components



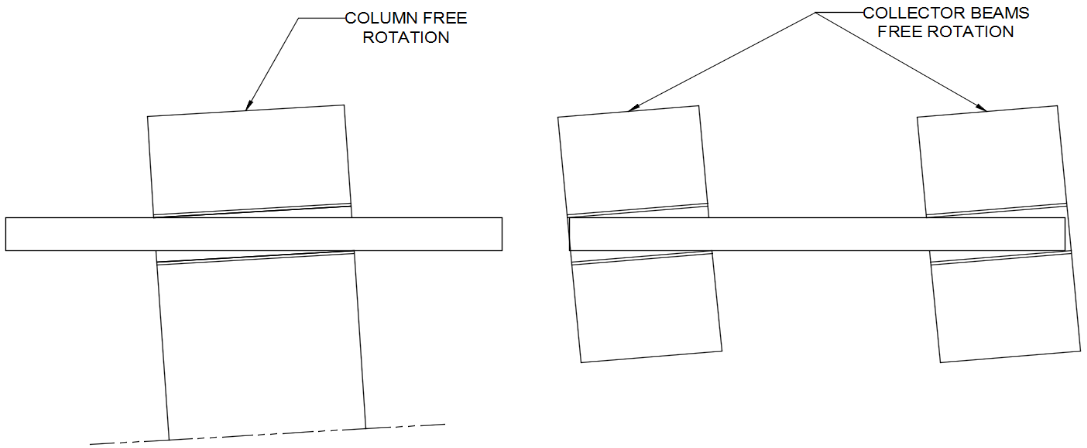
Collector-Beam-to-Column Connection



North Elevation View

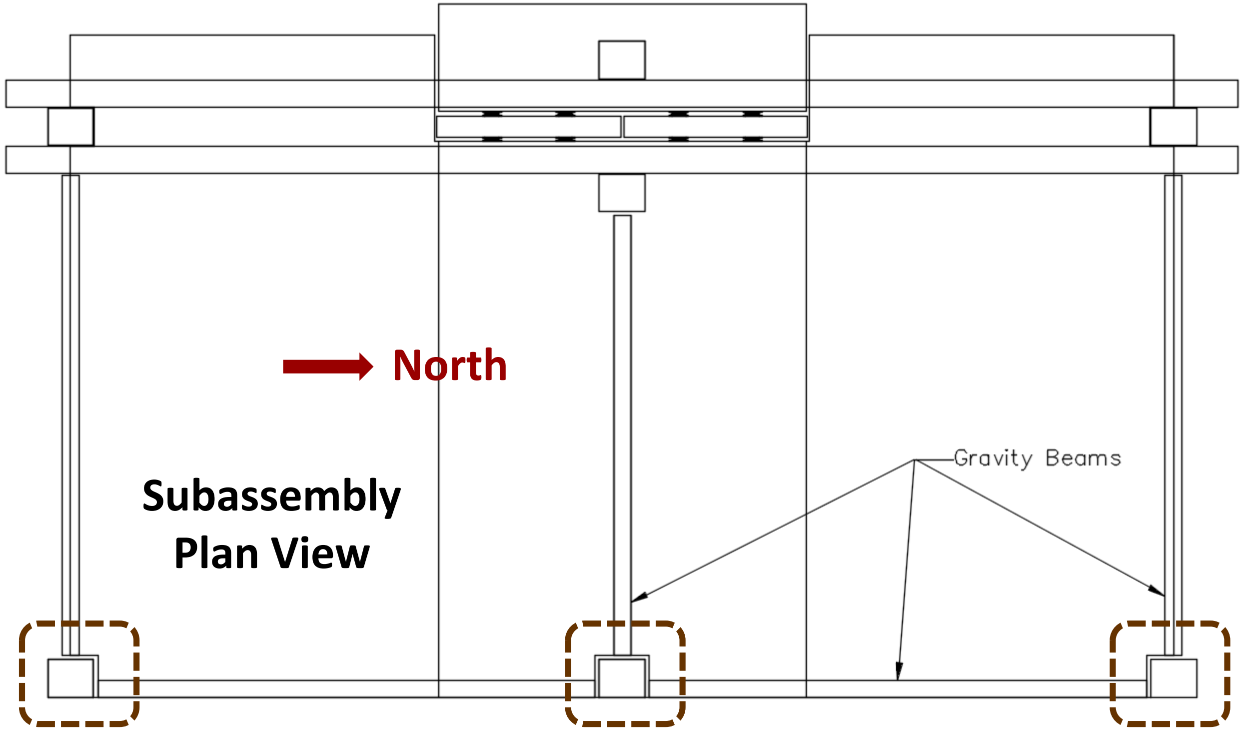


Out-of-Plane Deformation

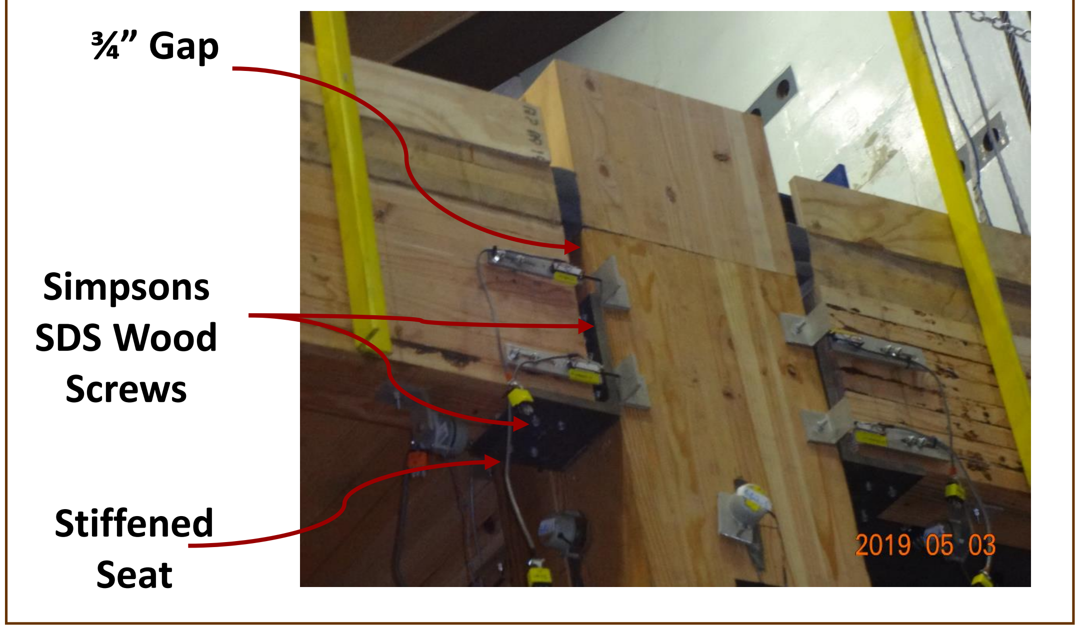


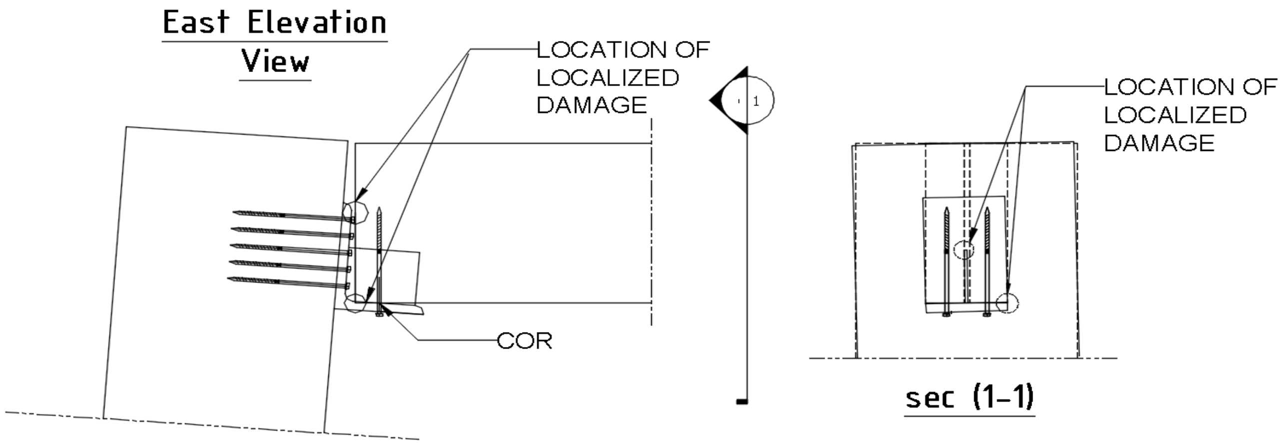
- In-plane free relative rotation
- 2.0% out-of-plane free rotation

Gravity-Beam-to-Column Connection



East Elevation View of Middle Column





- 7% in-plane deformation before contact
- 2.3% out-of-plane free rotation

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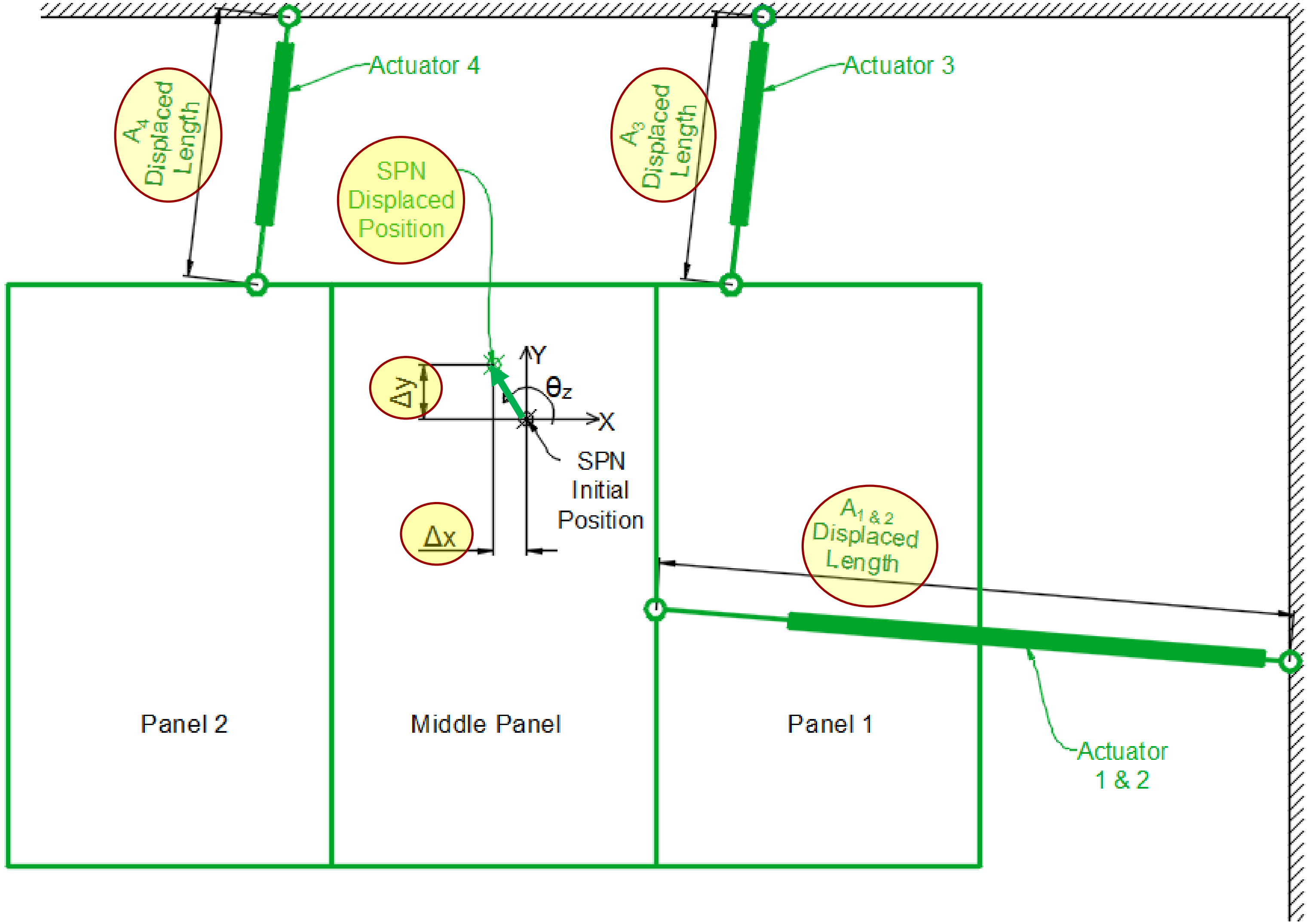
Test Subassembly Multi-Directional Kinematics



Plan View of Subassembly

Δx: SPN in-plane displacement Δy: SPN out-of-plane displacement

- Simulation Pivot Node (SPN)
  - At the center of the SC-CLT walls
  - Used as the test specimen control node associated with the subassembly degrees of freedom (DOF)

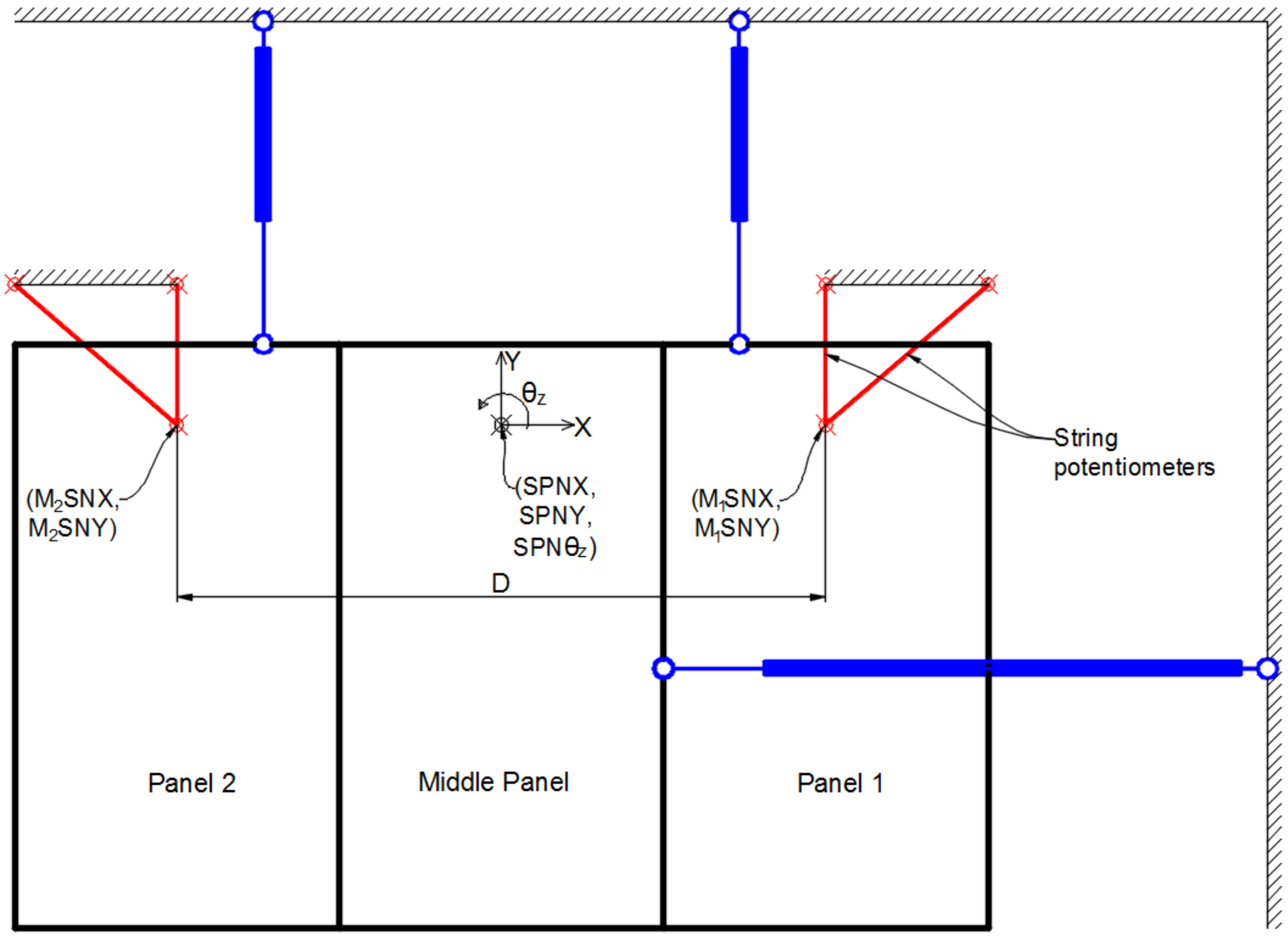
Multi-Directional Control Implementation Challenges:

- Multi-directional SPN displacements need to be imposed
- Coupled Actuator motion-3D displacements of SPN
- Flexibility in the test specimen CLT floor diaphragm and actuator attachment fixtures

Multi-Directional Control Implementation Solution

- Establish an SPN-Actuator structure node (ASN) DOF relationship using a series of sensors (MSN) on the CLT floor diaphragm

Measured SPN Displacement Feedback



- **SPN** movement determined from **real-time continuous feedback** of the global coordinates of two measurement-structural nodes (**M_1SN** and **M_2SN**)

$$SPN^{cfm}X = \frac{1}{2} M_1SNX + \frac{1}{2} M_2SNX$$

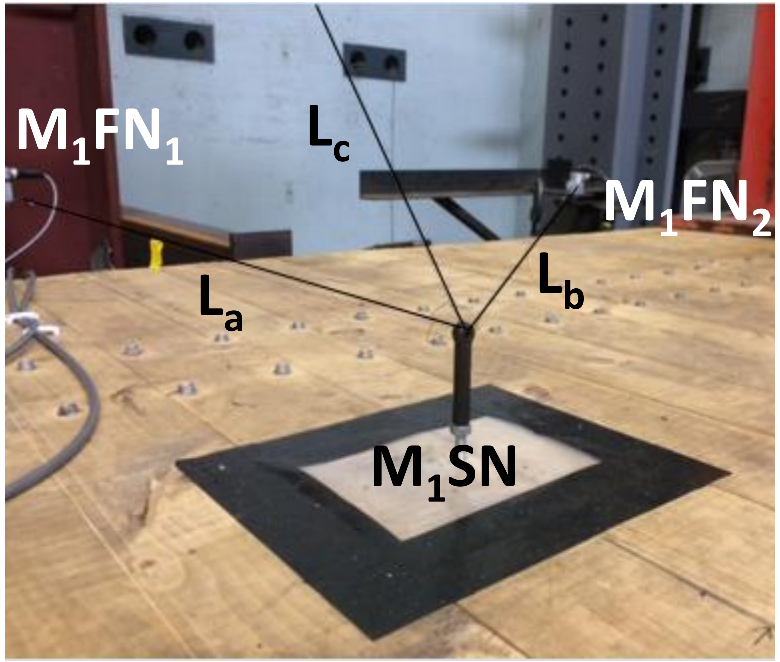
$$SPN^{cfm}Y = \frac{1}{2} M_1SNY + \frac{1}{2} M_2SNY$$

$$SPN^{cfm}\theta_z = \frac{1}{D} [M_1SNY - M_2SNY]$$

*SPN: Structure-physical node (control node)
*cfm: calculated from measurement

M_1SN Global Coordinates

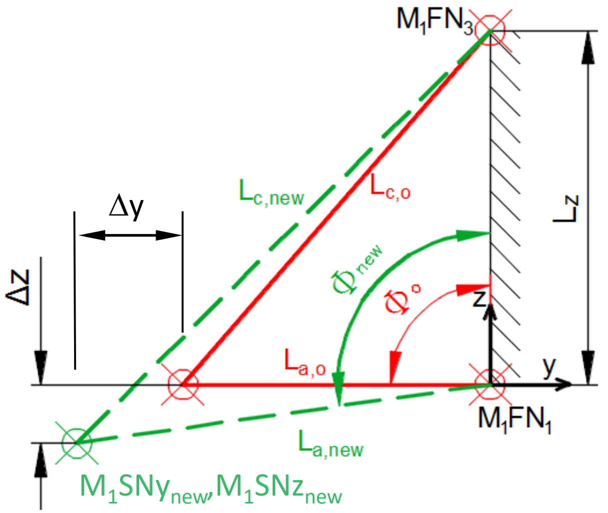
Sensors Arrangement for M_1SN



- Exact solution of M1SN displaced position based on sensors arrangement using the trigonometric law of cosines and sines

- $L_{a,o}$ and $L_{b,o}$: Initial string potentiometer length
- $L'_{a,new}$ and $L'_{b,new}$: Measured displaced string potentiometer length
- M_1FN_1X and M_1FN_1Y: Global coordinates of measurement fixed node of string potentiometer 1

Vertical Displacement



$$\Phi_{new}=f(L_{a,new}, L_{c,new}, L_z)$$

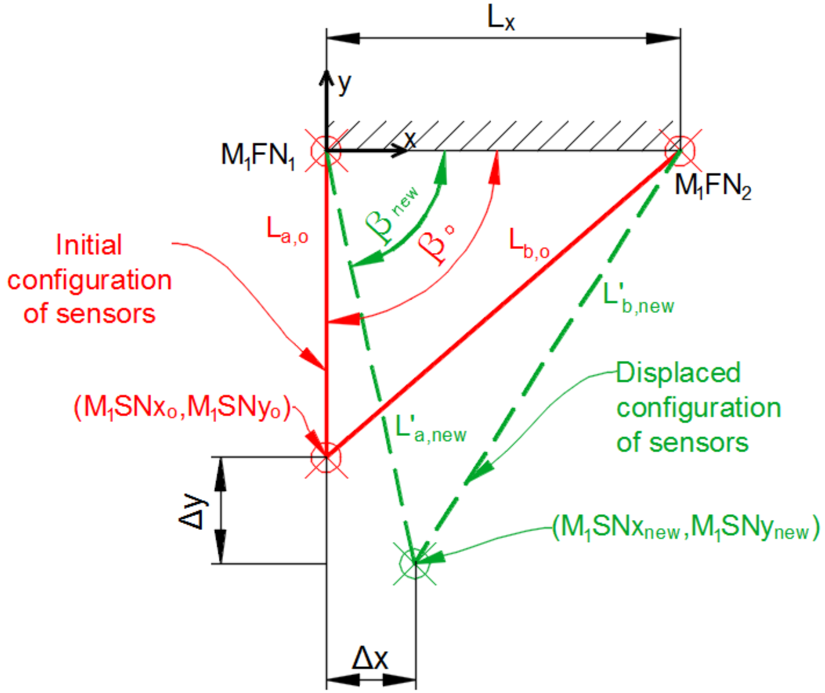
$$\beta_{new}=f(L'_{a,new}, L'_{b,new}, L_x)$$

- **Local in-plane displacement of M_1SN**

$$M_1SNx_{new} = L'_{a,\,new} \cos(\beta_{new})$$

$$M_1SNy_{new} = -L'_{a,\,new} \sin(\beta_{new})$$

Planar displacement

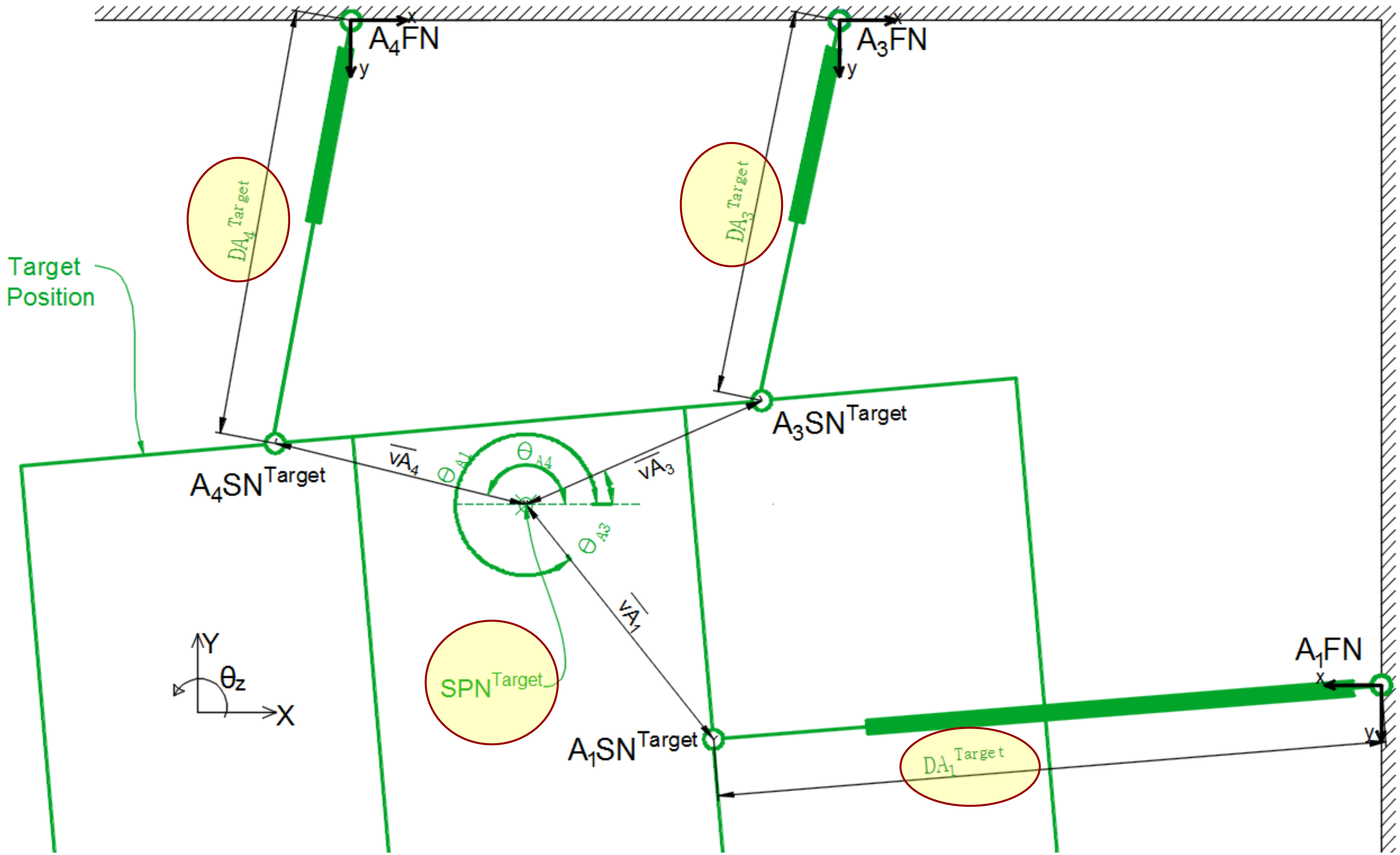


- **Displaced position of M_1SN in Global Reference Coordinates**

$$M_1SNX = M_1SNx_{new} + M_1FN_1X$$

$$M_1SNY = M_1SNy_{new} + M_1FN_1Y$$

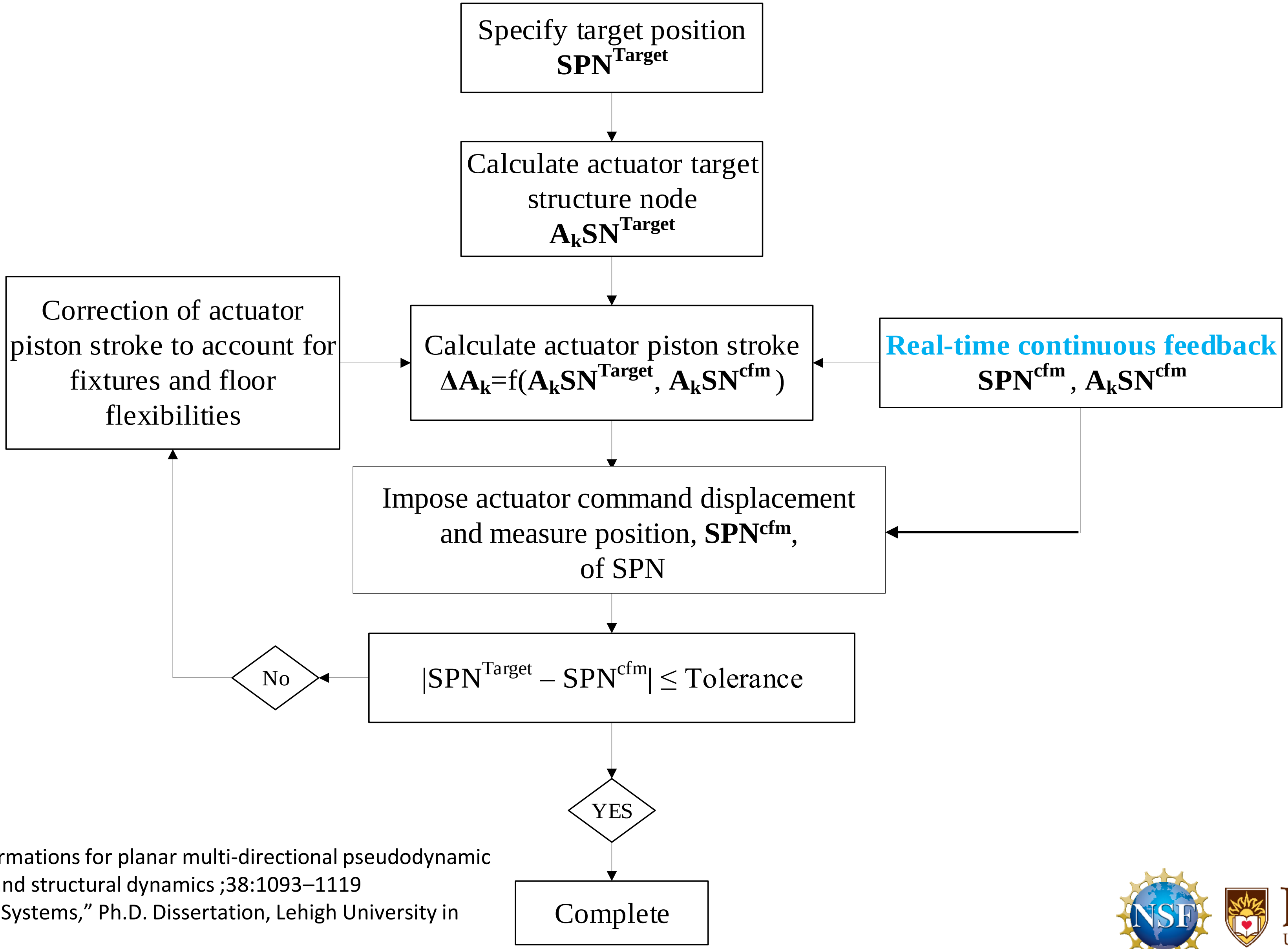
Actuator Displacement



- Assuming rigid floor diaphragm (**Corrected**):
  - ➢ $A_kSN^{Target} = f(SPN^{Target}$, diaphragm geometry)
- Using Pythagoras' Theorem:
  - ➢ $DA_k^{Target}=f(A_kSN^{Target}, A_kFN)$
- Actuator Piston Stroke:
  - ➢ $\Delta A_k=DA_k^{Target} - DA_k^{cfm}$

- A_kSN: k^{th} actuator structure node
- A_kFN: k^{th} actuator fixed node
- DA_k: k^{th} actuator distance between ASN and AFN

Test Subassembly 3D Control Algorithm



Mercan et al.2009 ,"Kinematic transformations for planar multi-directional pseudodynamic testing," Earthquake engineering and structural dynamics ;38:1093–1119
Amer, A. "Seismic Performance of CLT Systems," Ph.D. Dissertation, Lehigh University in progress (~ Dec. 2020)

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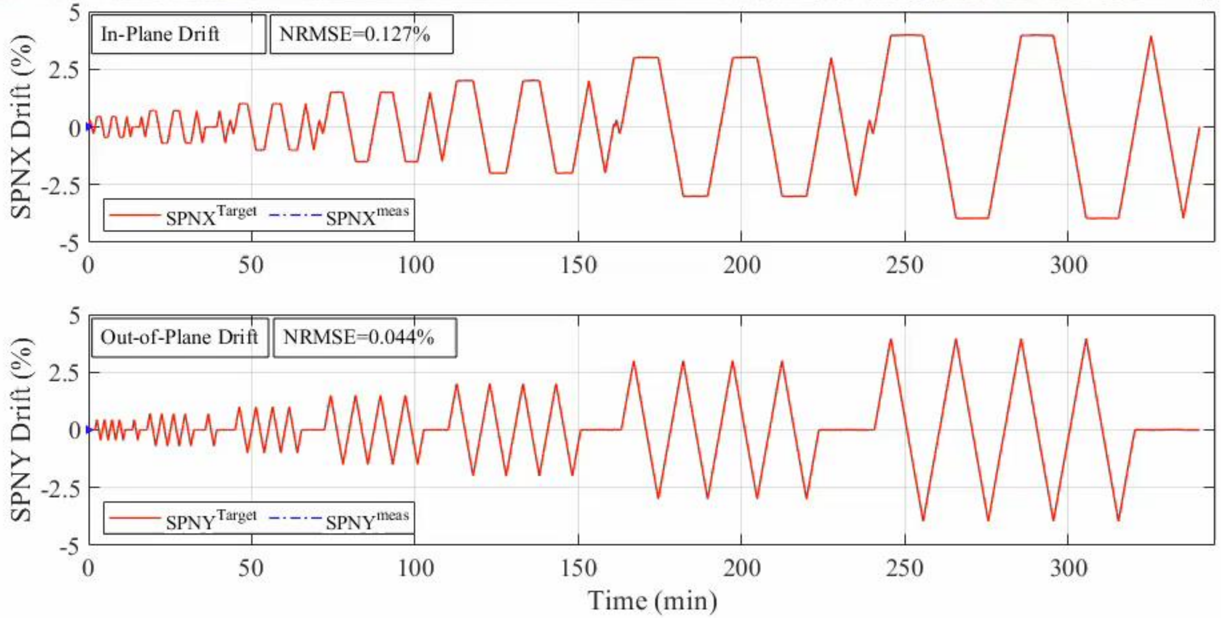
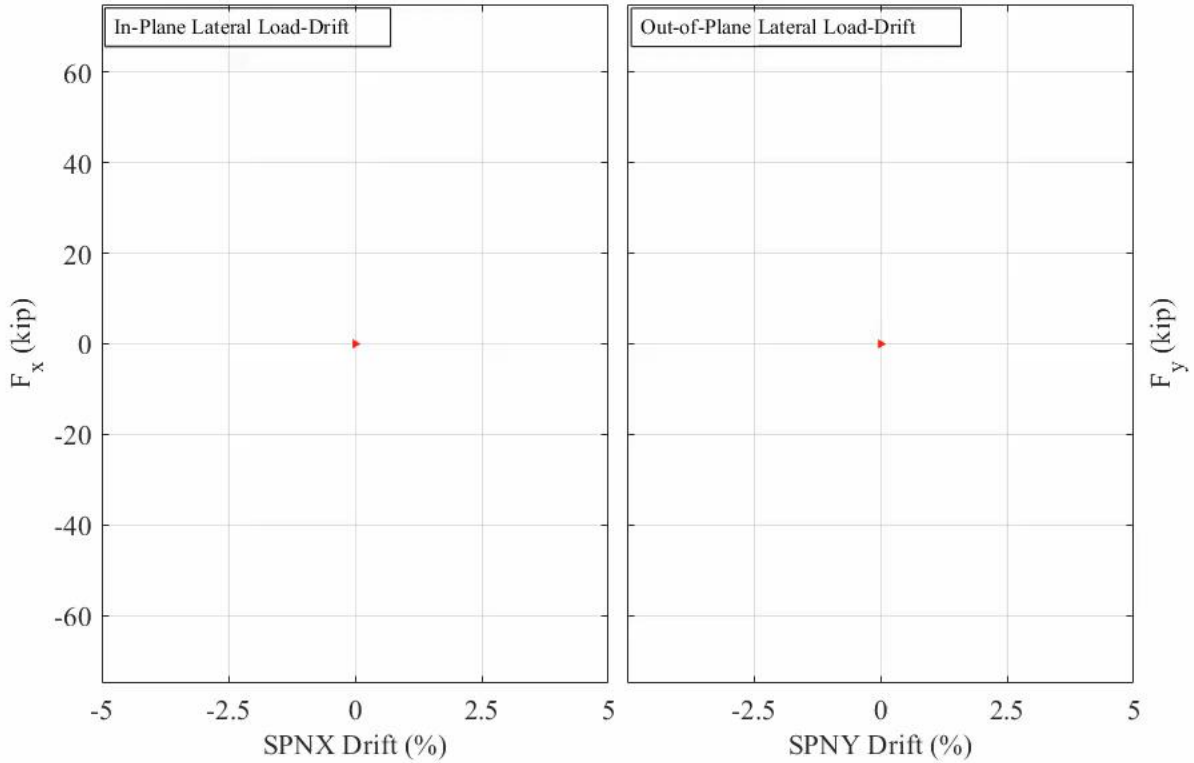
Experimental Substructure (0.625-Scale)

South Wall Panel

North Wall Panel



Comparison of Target vs. Measured Subassembly Drift



Multi-Directional

Cyclic Testing of CLT Subassembly

SC-CLT Wall Damage State at 4% Drift

Excessive corner rounding due to localized bearing failure

Outer ply buckling

Corner crushing

Outer ply buckling and delamination

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Summary and Conclusions

- Multi-directional test performed on timber subassembly
- Kinematic compensation used to impose specimen multi-directional displacement history
- Results show high degree of accuracy achieved for specimen displacement
- Combination of in-plane and out-of-plane loading has an effect on SC-CLT walls

Thank You

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