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Composite and Hybrid Mass Timber-Steel Floors: Engineering by Connections Design and Detailing

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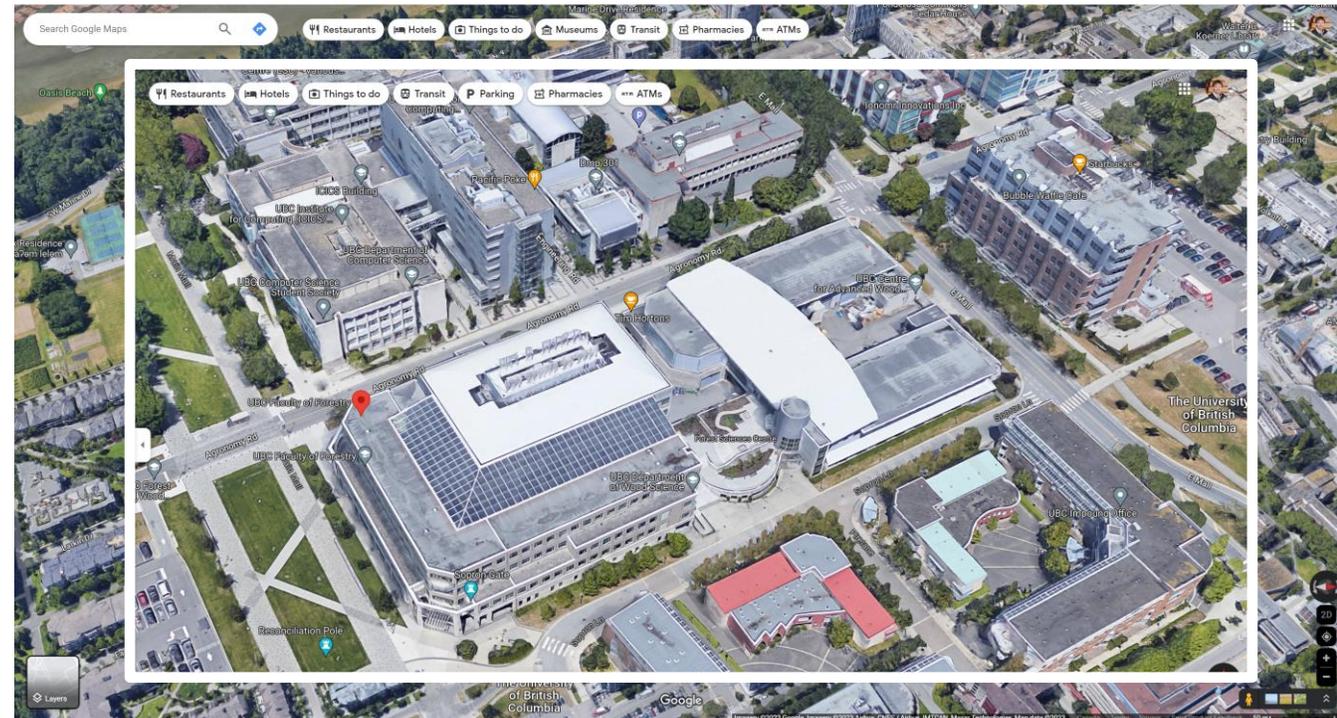
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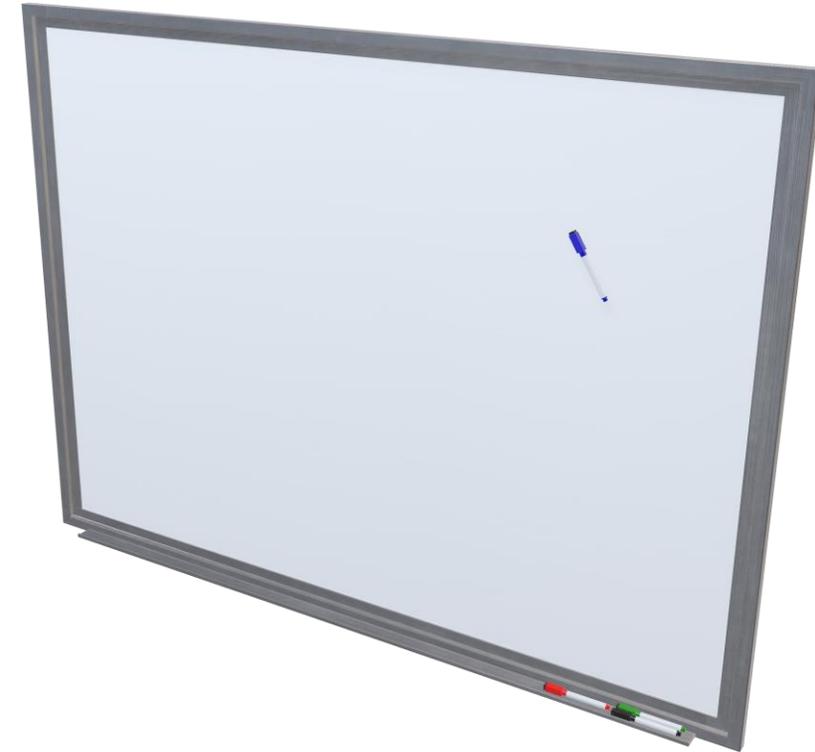
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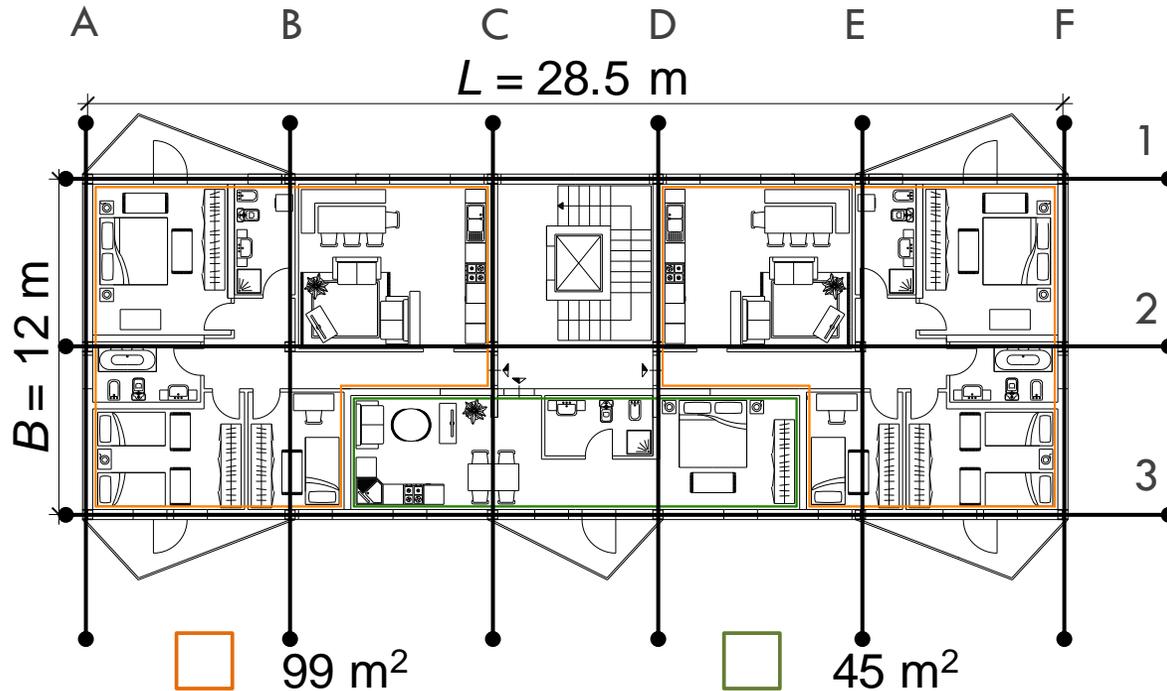
Summary

- HYBRID AND COMPOSITE TIMBER-BASED FLOORS: INTRODUCTION (WHY?)
- MASS TIMBER-STEEL COMPOSITE FLOORS: MECHANICAL CONSIDERATIONS, ROLE OF CONNECTIONS, STATIC BEHAVIOUR (BASED ON MULTI-YEAR RESEARCH)
- MASS TIMBER-STEEL DIAPHRAGMS: SEISMIC LOADING (BASED ON MULTI-YEAR RESEARCH)
- DYNAMIC RESPONSE: VIBRATION PERFORMANCE (ONGOING)



Floors: Overview – Architectural and Performance-Based Design Aspects

Common Residential Buildings



Highlights

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- Use of a standardized gridlines (organization of the space)
- Maximize number of apartments (change of needs)

Building Design Constraints



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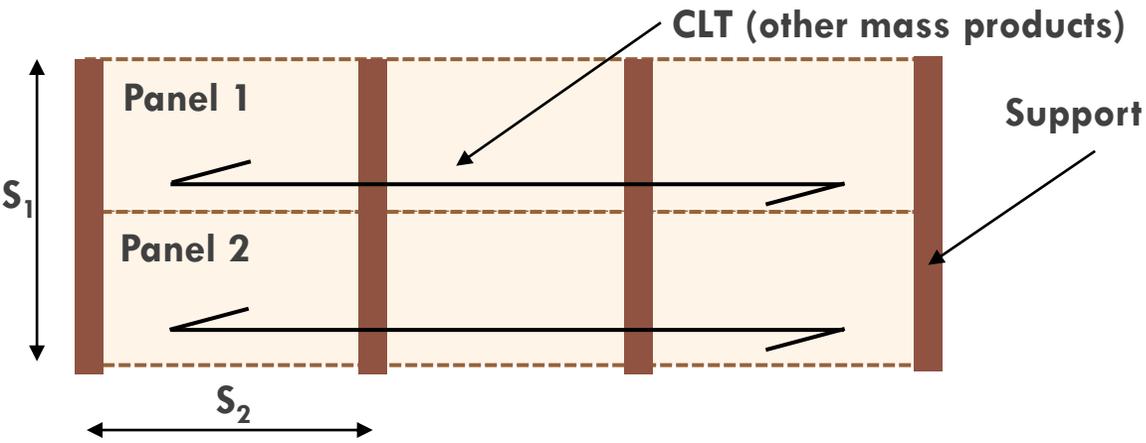
Requirements

- Energy-efficiency
- Fire-rate performance
- Acoustic performance
- Access to the plumbing and heating systems (MEP)
- Occupancy of the building
- Policies (e.g., use of land)

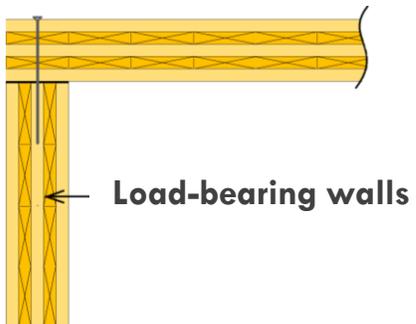
Floors: Conventional versus Hybrid Systems

Mass Timber Floors

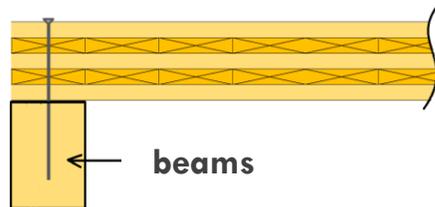
Engineering Practice: Linear-Type Supports



Supports: Type A



Supports: Type B



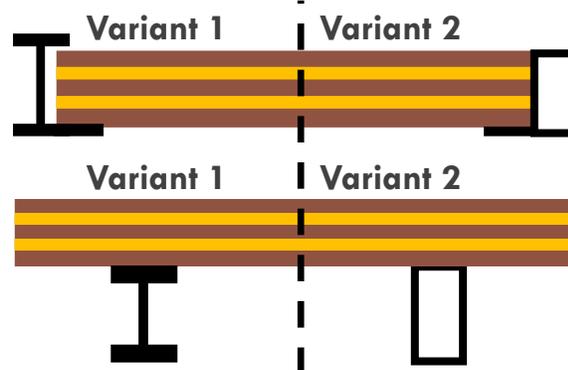
Pictures Credits: FPIInnovations

Hybrid Mass Timber-Steel Alternative Floors

Popular solutions in many Countries around the world



Picture Credits: Ermanno Acler



Asymmetric steel profiles

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Regular symmetric steel profiles

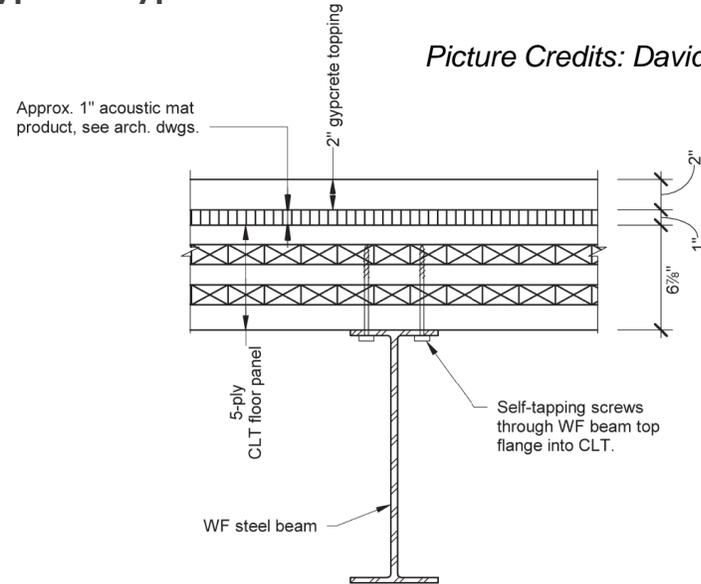
Floors: Hybrid Systems

Why hybrid Floors?

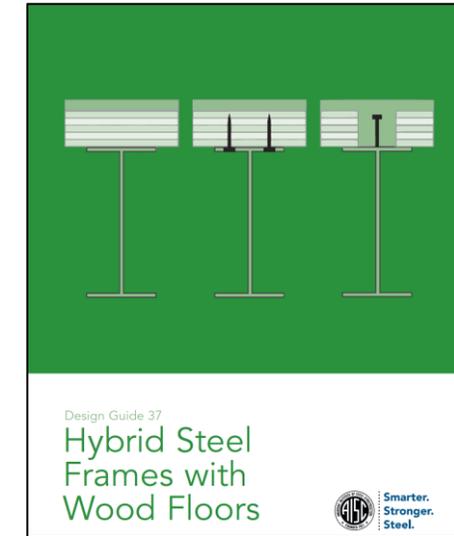
- **Material efficiency**
- Fabrication process
- Modularity
- Seismic resiliency
- Aesthetic
- **Large inventory of materials**
- Lightweight
- Long beam spans

Design of Hybrid Floors

Typical T-type Cross-Section



Design guidebook

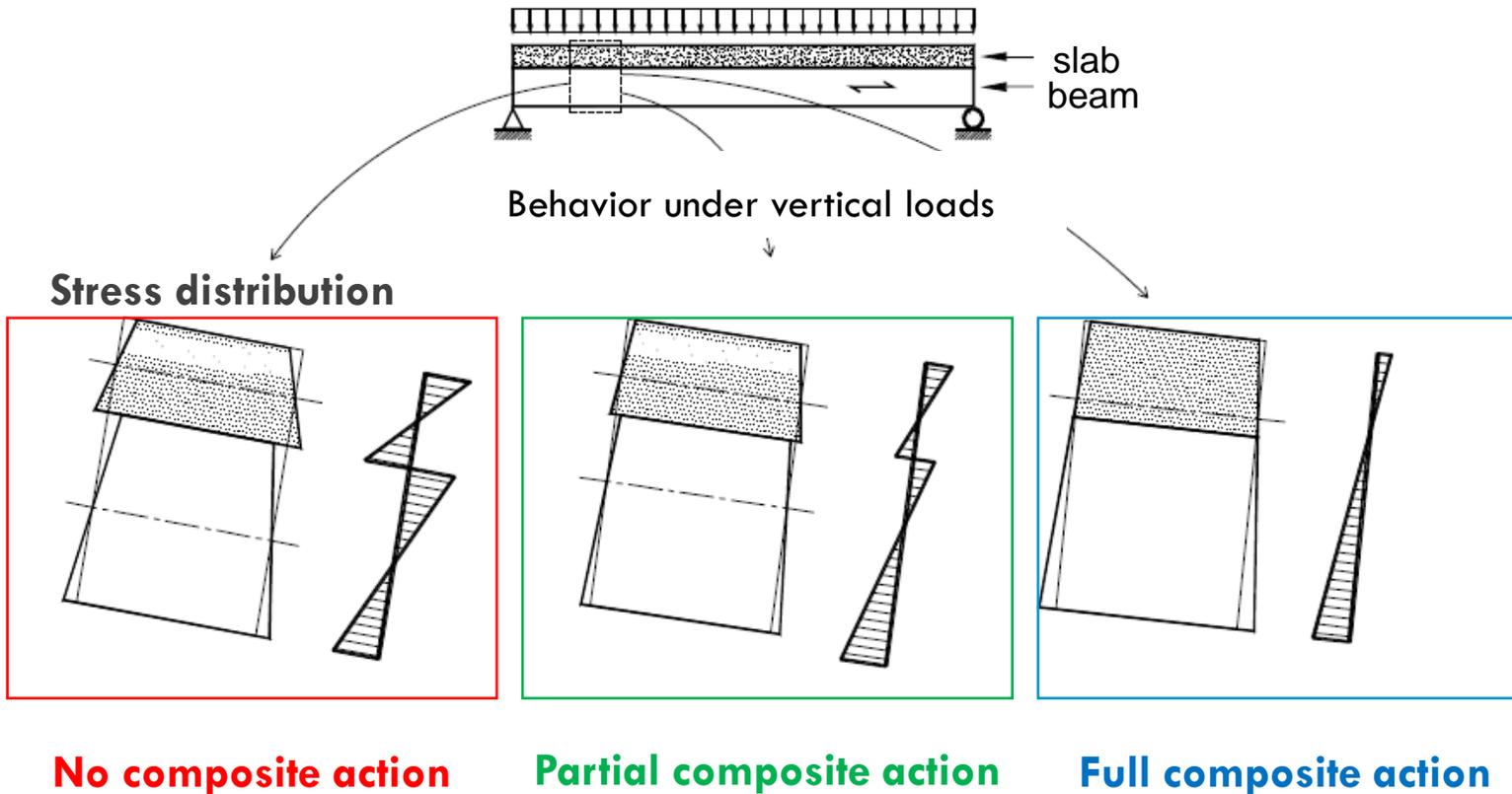


- Design of the CLT panels like one-way elements multi-supported on steel beams – span direction along the building width
- Slab: use surface splines or other joints to connect the panels at their edge (design per timber-to-timber or steel-to-timber connections - CSA-086)
- Beam-to-slab: use fasteners to speed up construction; dimension and spacing to ensure transfer of shear forces from the diaphragms to the braced frames (design per steel-to-timber connections – CSA-086)

Floors: Composite Systems

Why composite floors?

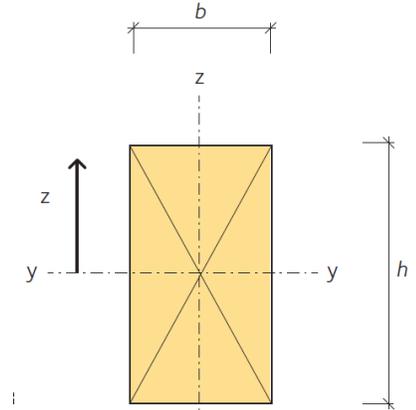
Mechanical behavior – Same beam and slab bearing direction



Elements in bending

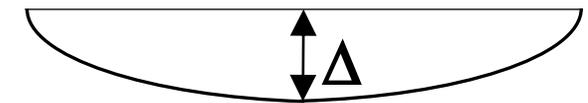
ULS

$$\sigma = \frac{M \cdot z}{I_y}$$



SLS

$$\Delta = \frac{5}{384} \frac{\omega L^4}{E I_y} + \frac{1}{8} \frac{\omega L^2}{G A}$$

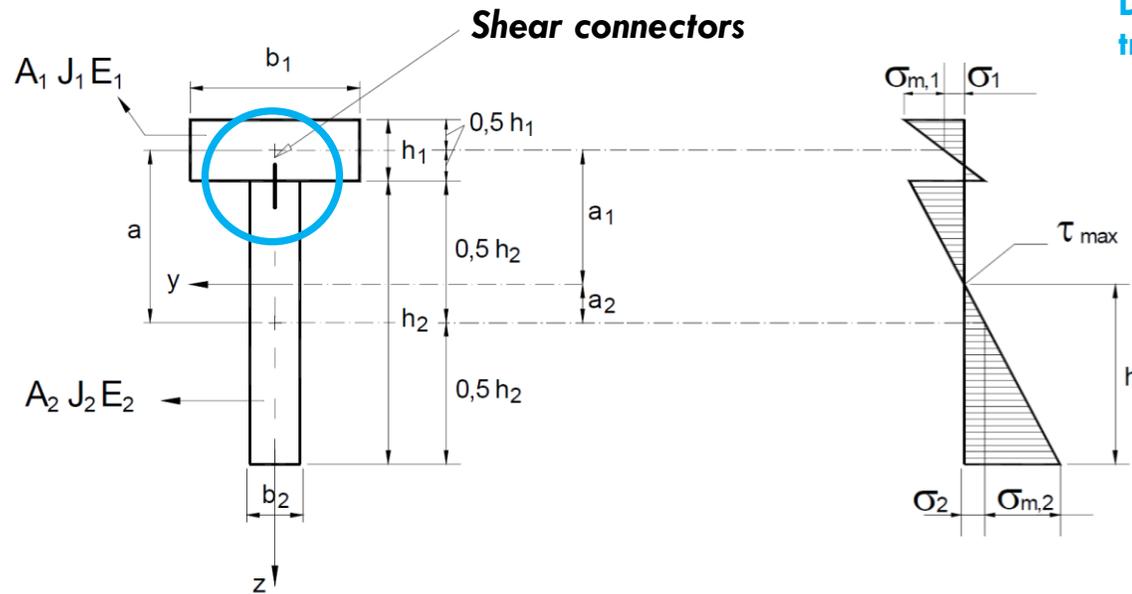


If h is small so it will be I_y ($= \frac{1}{12} b h^3$)

Reduced stress levels and deflection can be attained increasing I_y , thus h

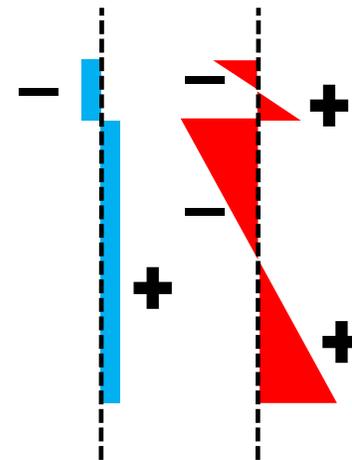
Floors: Composite Systems

Engineering Practice for composite floor systems – Partial composite action



Due to shear transfer

Due to bending in elements



Highlights

- **ULS:** normal stress distribution causes reduction of stresses at the interface between slab and beam (compressed side in the beam and tension side in the slab)
- **SLS:** Bending stiffness improved thanks to the term EA (axial stiffness in slab and beam)

NORMAL STRESS - SLAB

$$\sigma_1 = \gamma_1 E_1 a_1 \frac{M}{EJ_{eff}}$$

$$\sigma_{m,1} = \frac{h_1}{2} E_1 \frac{M}{EJ_{eff}}$$

NORMAL STRESS - BEAM

$$\sigma_2 = \gamma_2 E_2 a_2 \frac{M}{EJ_{eff}}$$

$$\sigma_{m,2} = \frac{h_2}{2} E_2 \frac{M}{EJ_{eff}}$$

WHERE

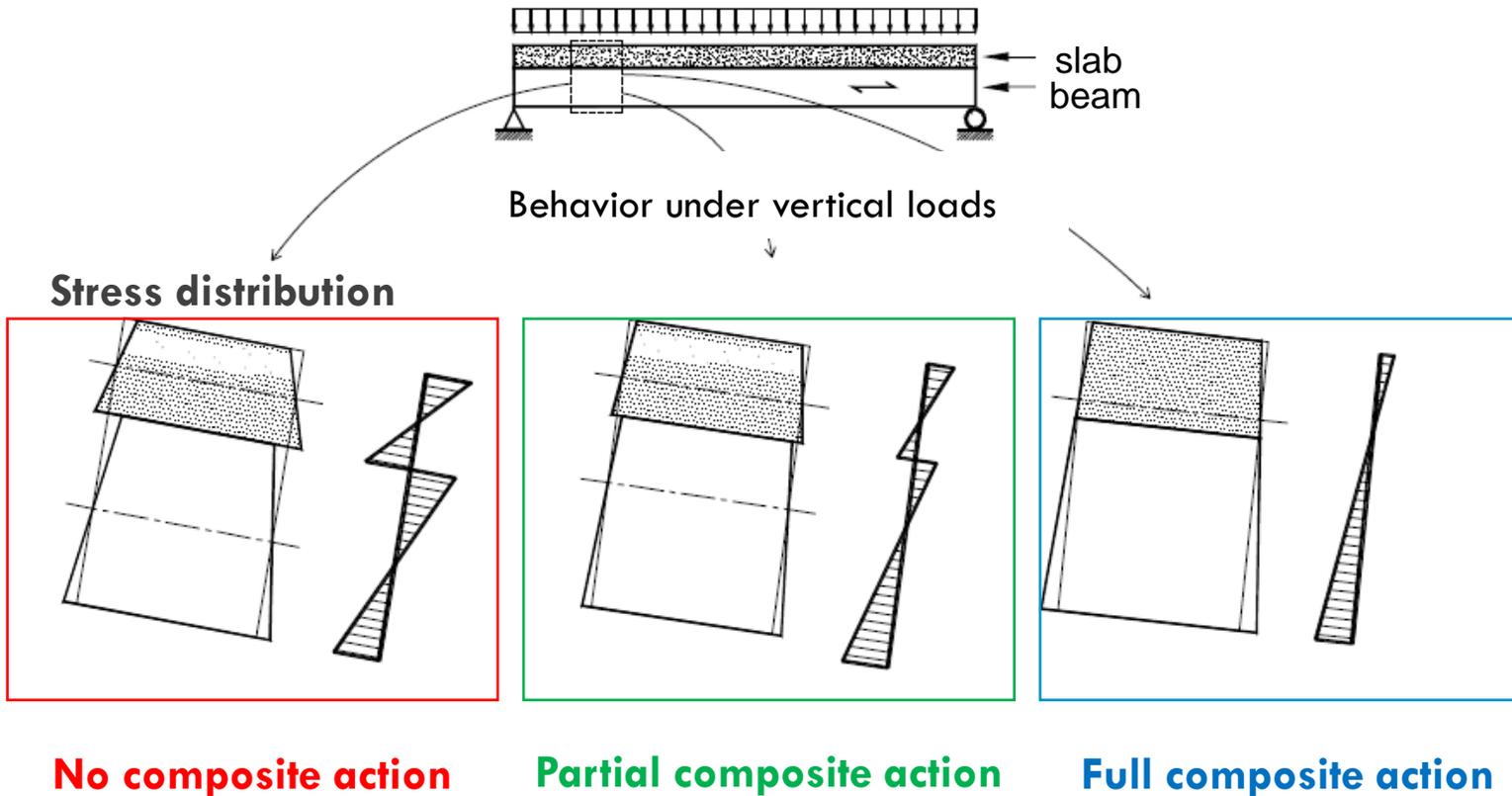
$$\gamma_1 = \frac{kl^2}{1 + \pi^2 E_1 A_1} \quad \gamma_2 = 1 \quad a_1 = r - a_2 \quad a_2 = -\frac{\gamma_1 E_1 A_1 r}{E_2 A_2 + \gamma_1 E_1 A_1}$$

$$(EJ)_{ef} = \sum E_i J_i + E_2 A_2 a_2^2 + \gamma_1 E_1 A_1 a_1^2$$

Floors: Composite Systems

Why composite floors?

Mechanical behavior – Same beam and slab bearing direction



Where do we find usual applications?

Steel-concrete composite floors



Picture Credits: Structville

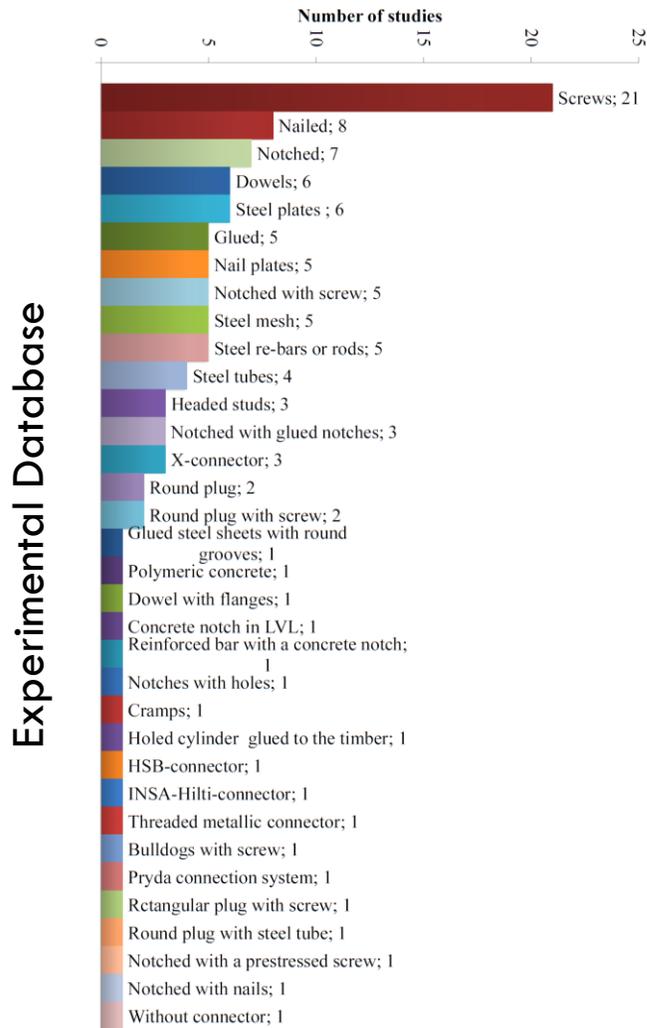
Timber-concrete composite floors



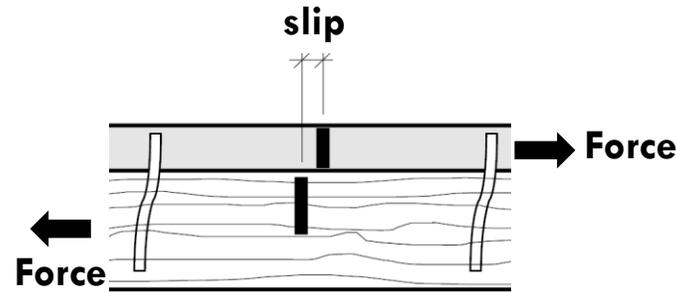
Picture Credits: Rhomberg Ventures

Composite Steel-Timber Floors: Shear Connectors

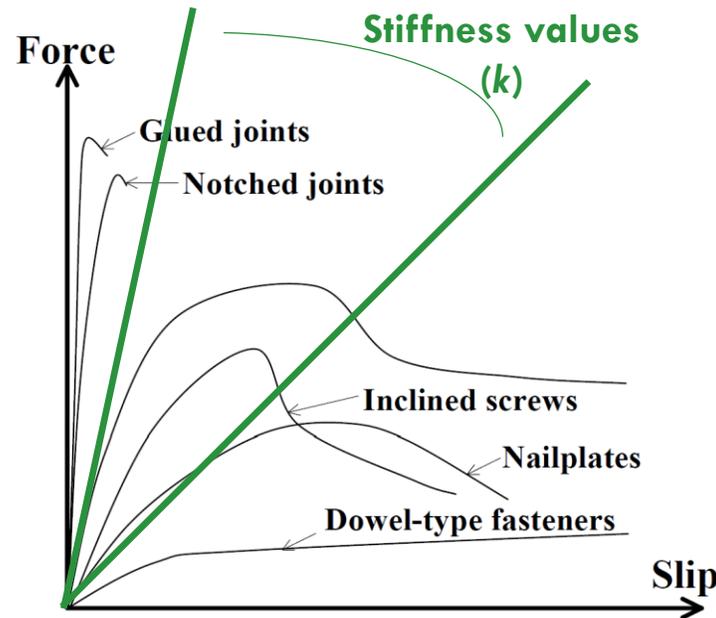
Timber-Concrete Composite Floors – Connections behaviour



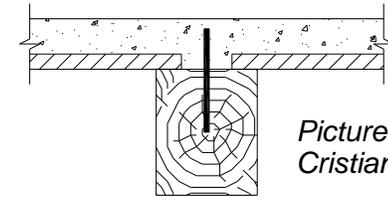
Picture Credits: Alfredo Dias



Picture Credits: Hans Joachim Blaß



Design Procedures for TCC



Picture Credits: Cristiano Loss

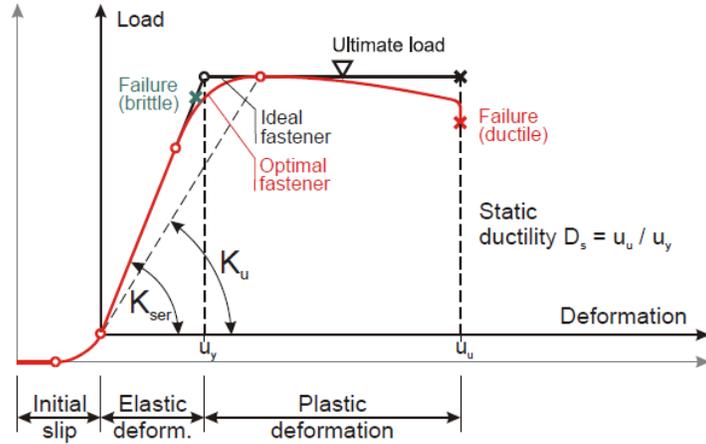
Guidance included in the new version of the CSA-086 and Eurocode 5, including a section on shear connectors



Empirical model to estimate the stiffness of some mechanical dowel-type fasteners

Composite Steel-Timber Floors: Beam-to-Slab Connections

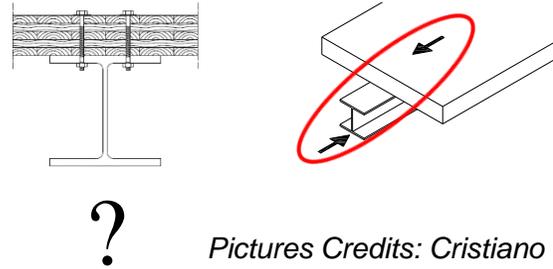
Design Considerations



Coordinate system for modeling and analysis
 Coordinate system for tests (real behaviour)

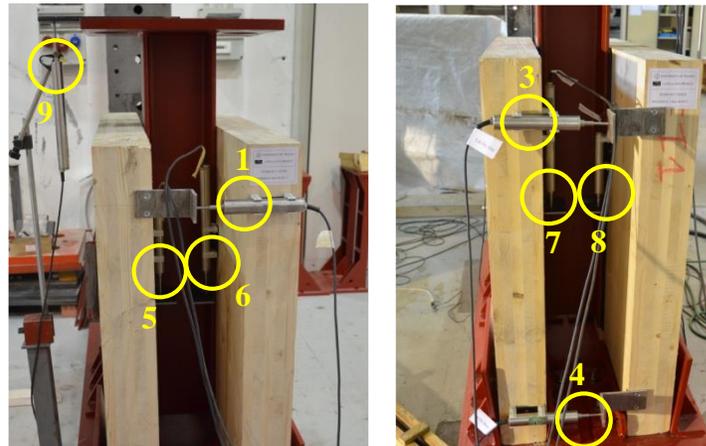
- Technical details for mechanical connections are available, especially for fasteners in timber-to-timber and steel-to-timber shear configurations
- However, data/models on stiffness values (slip modulus) are still limited
- The design of joints also points to using several slender fasteners

Testing Program – New Solutions



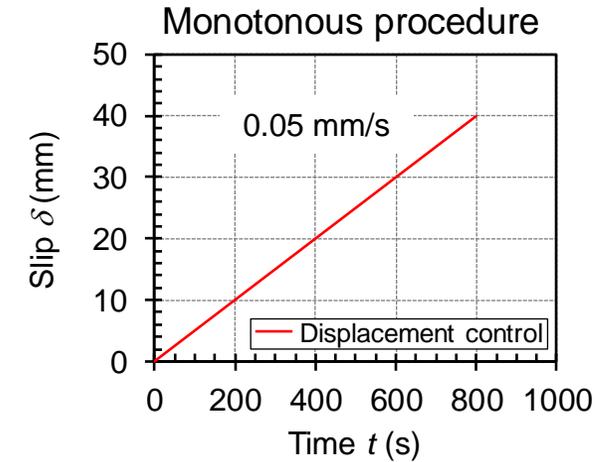
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Push-out tests: Two shear planes

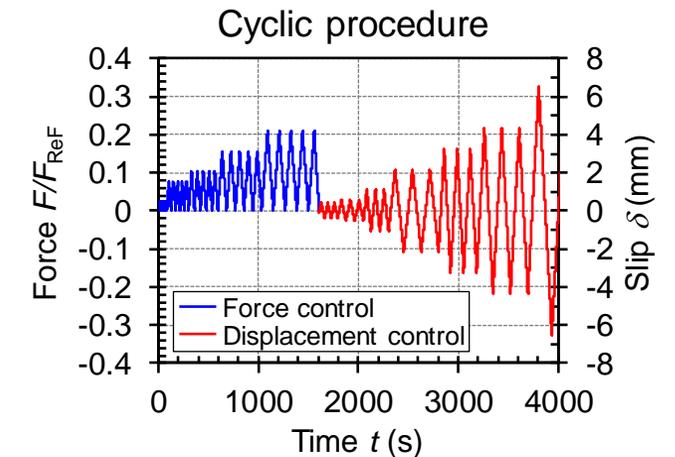


Testing Protocols

Type A



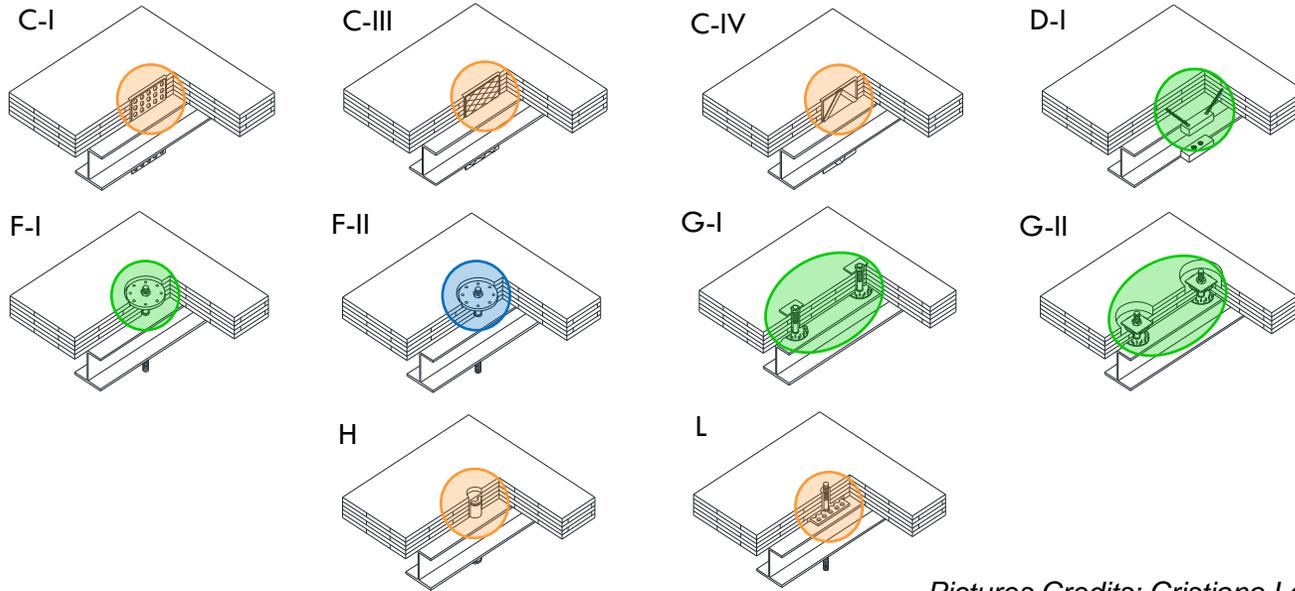
Type B



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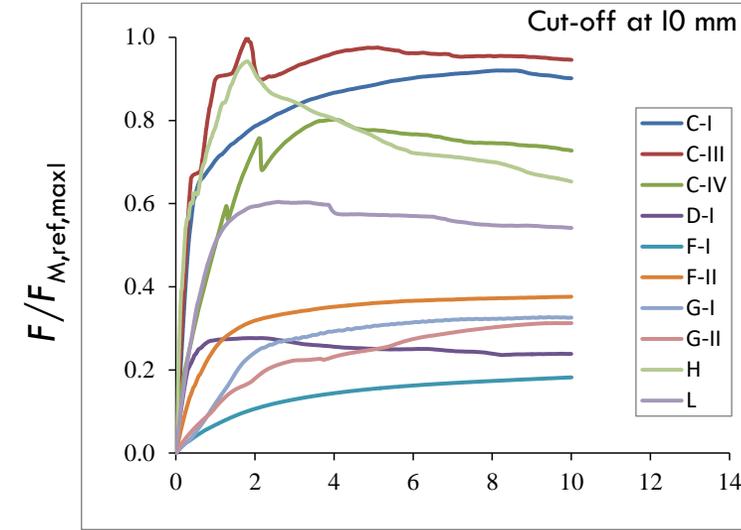
Composite Steel-Timber Floors: Beam-to-Slab Connections

Prototypes of Beam-to-Slab Connections



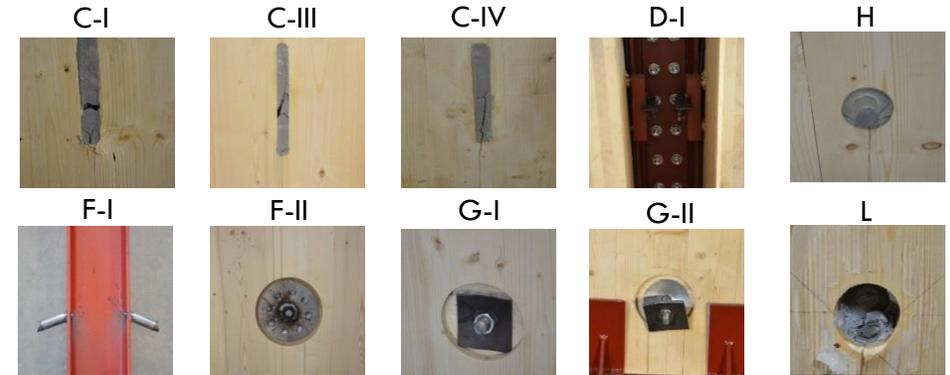
Pictures Credits: Cristiano Loss

Load-Slip Curves (Monotonic)



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Slip δ [mm]



Highlights

- Testing matrix includes more than 20 connector arrangements
- Checking installation procedure and tolerance: use of standard equipment and consultation with contractors

References

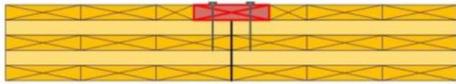
Loss, C., M. Piazza and R. Zandonini (2016). "Connections for steel-timber hybrid prefabricated buildings. Part I: Experimental tests." *Construction and Building Materials* 122: 781-795. DOI: 10.1016/j.conbuildmat.2015.12.002

Loss, C., M. Piazza and R. Zandonini (2016). "Connections for steel-timber hybrid prefabricated buildings. Part II: Innovative modular structures." *Construction and Building Materials* 122: 796-808. DOI: 10.1016/j.conbuildmat.2015.12.001

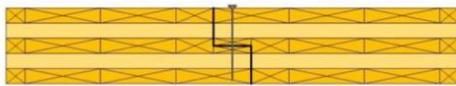
Composite Steel-Timber Floors: Slab Connections

Common practice

Pictures Credits: FPInnovations



Single surface spline



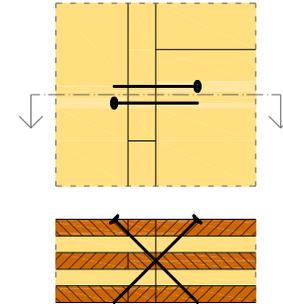
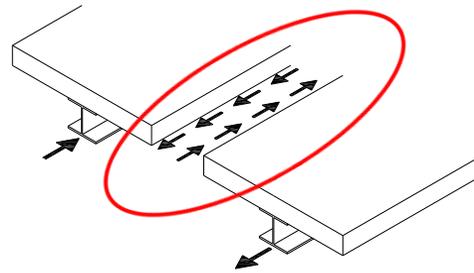
Half-lap joint

Other types are available and not shown here

- Very common to join CLT panels using self-tapping screws (STS)
- Configurations above apply through the removal of wood
- Require machining of the panels in the factory (production plants)
- Developed for platform-type CLT buildings (all wood)

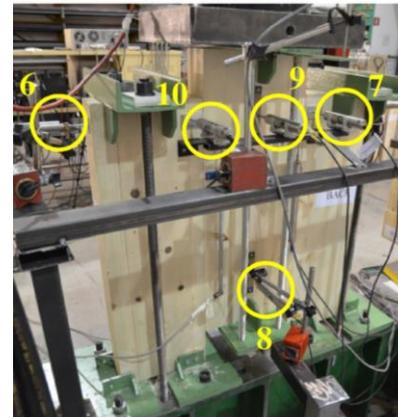
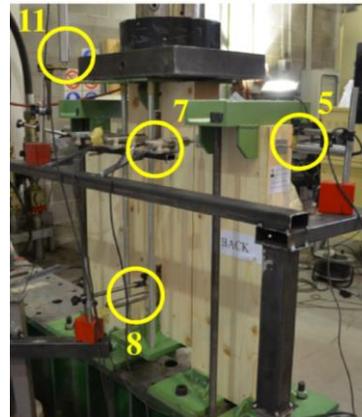
Testing Program – New Solutions

Panel-to-Panel Connections



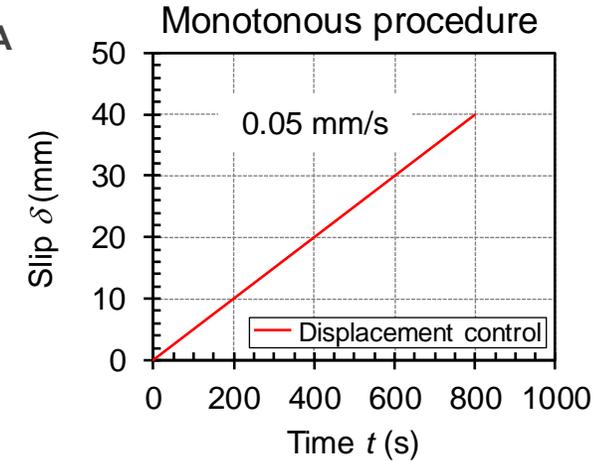
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Push-out tests: Two shear planes

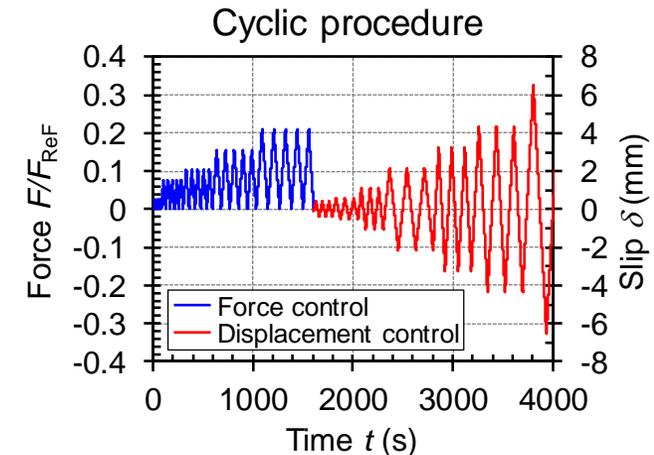


Testing Protocols

Type A

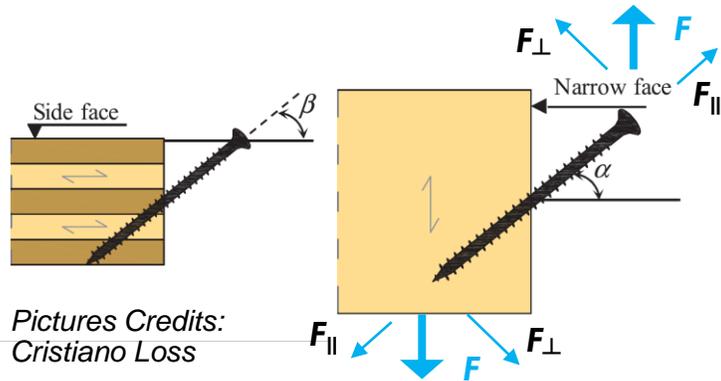


Type B



Composite Steel-Timber Floors: Slab Connections

Design Considerations



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Cristiano Loss

- Empirical models for calculating the slip modulus of STS suggest only axial slip modulus depends on their penetration length
- STS angle of insertion and penetration length can be affected by the thickness of the CLT panels
- The angle of insertion of STS determines axial and shear loading components and the mechanical reaction of the STS

Experimental Results

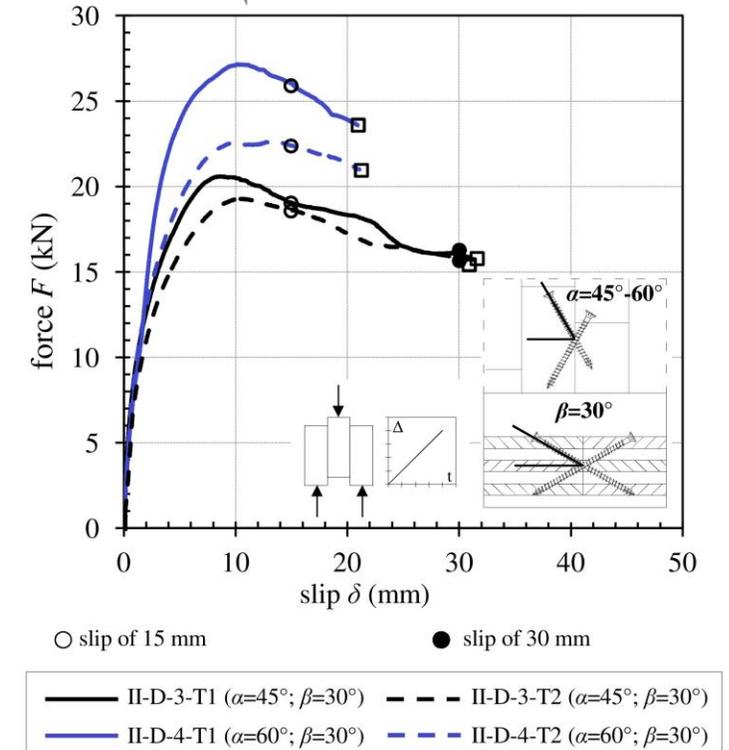
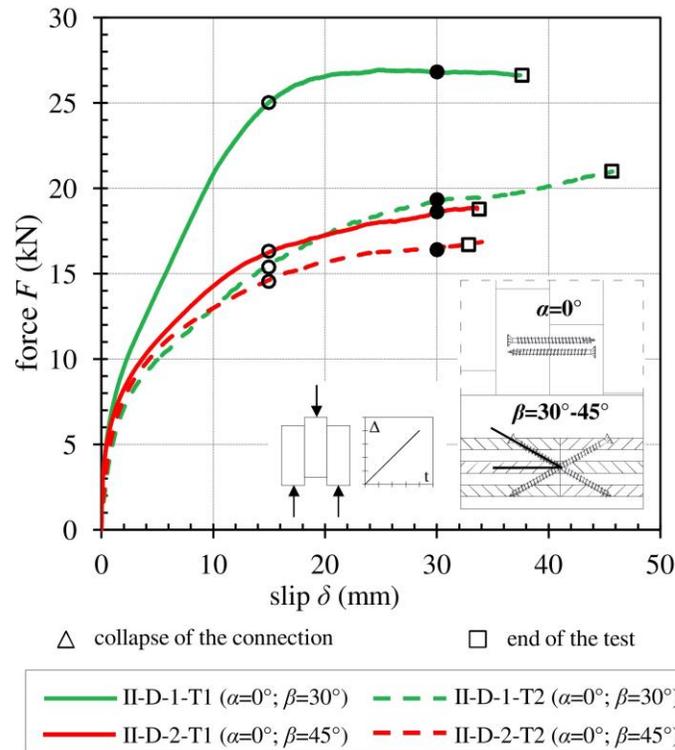


STS loaded perpendicular to their axes

Pictures Credits: Cristiano Loss



STS loaded in both perpendicular and parallel to their axes



References

Loss, C., A. Hossain and T. Tannert (2018). "Simple cross-laminated timber shear connections with spatially arranged screws." Journal of Engineering Structures 173: 340-356. DOI: 10.1016/j.engstruct.2018.07.004

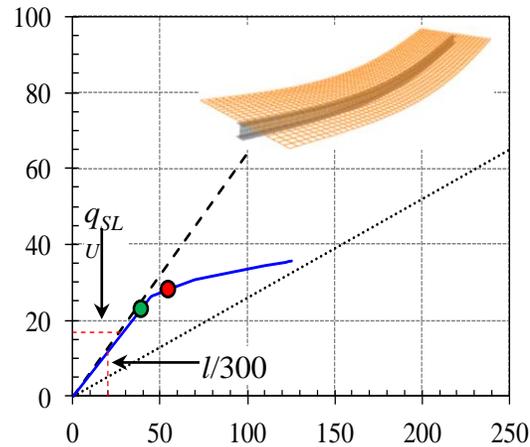
Composite Steel-Timber Floors: Conventional Design - Approach

Mechanical and design Considerations - Static

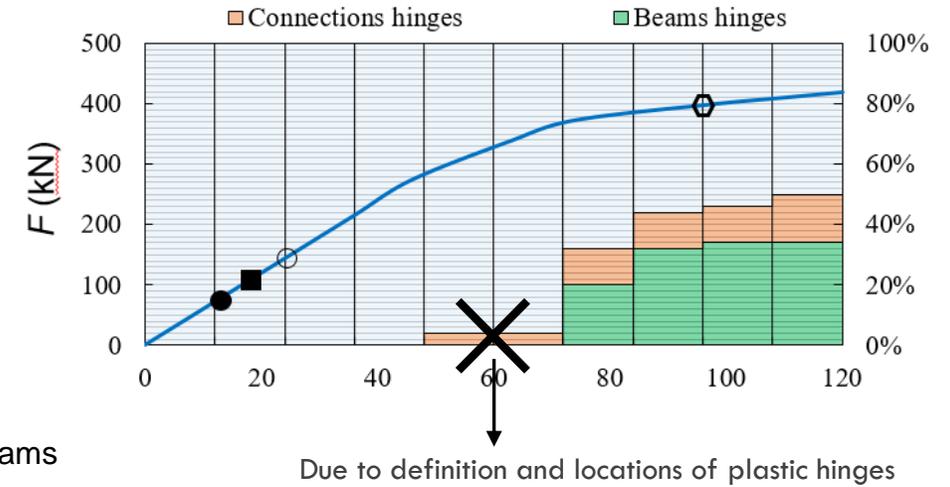
- Which connection works best?
- Any suggested arrangements for the connectors?
- To what extent does common elastic analysis of composite floors apply here?
- Which failure modes will govern at the system level (ULS)?
- How can I make this system cost-effective?

Pre-design (governed by the deflection limitation)

Finite-Element Method – Spacing Optimization



- Plastic deformation of steel beams
- Plastic deformation of connections



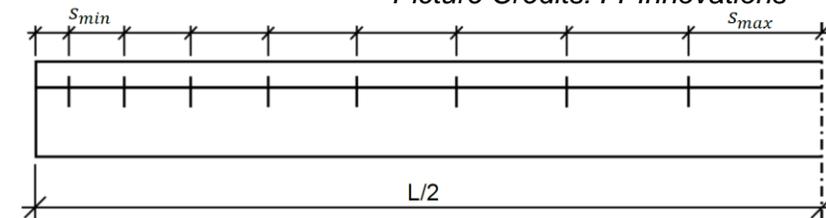
Due to definition and locations of plastic hinges

Cross-section - Profiles



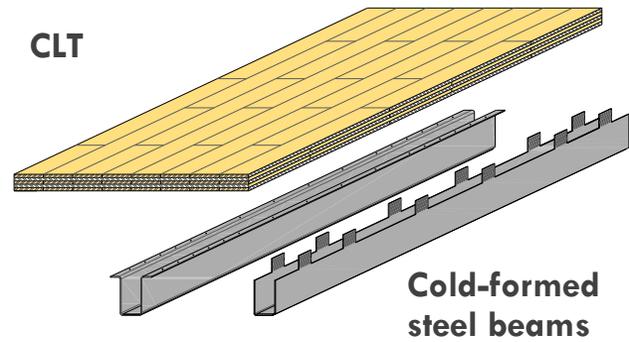
Linear Variation of Spacings

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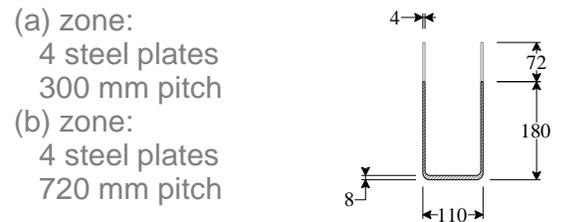
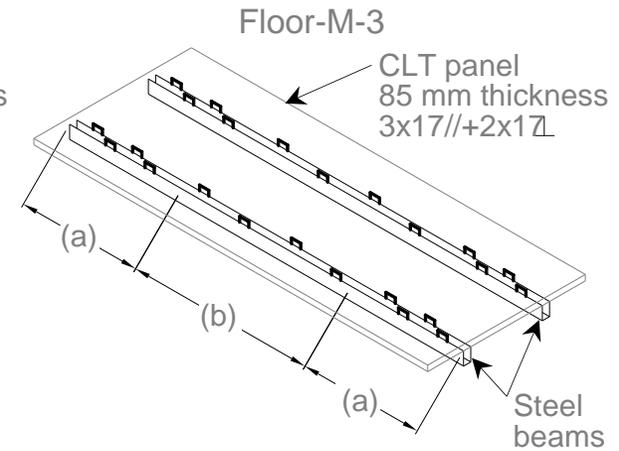
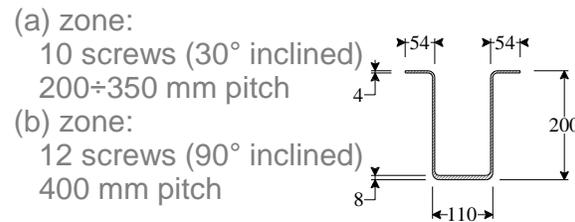
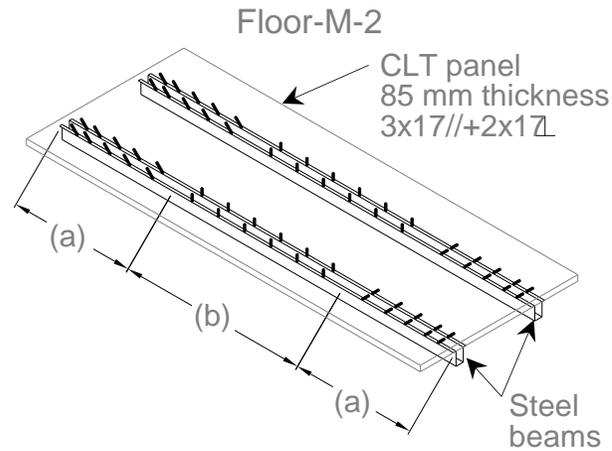
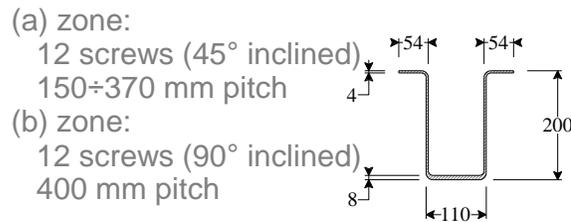
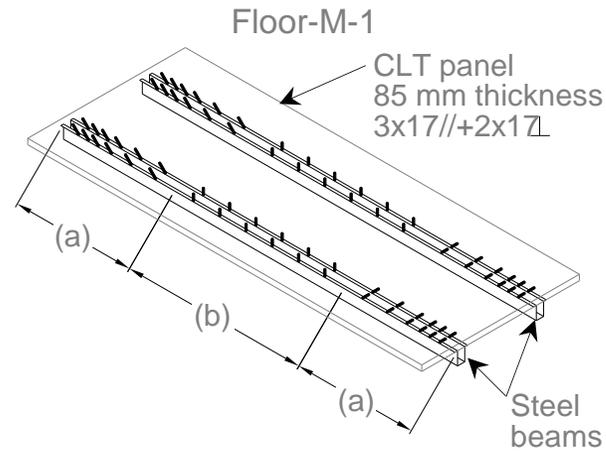


Composite Steel-Timber Floors: Conventional Design - Solutions

Components



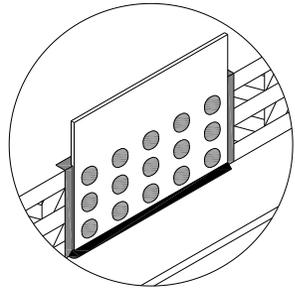
System-Level Design Optimization



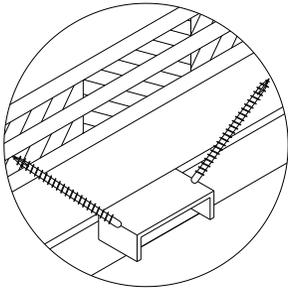
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Connections

Steel drilled plates – epoxy-based grout



Inclined STS



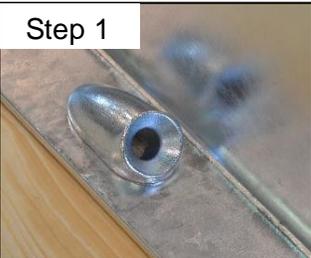
Pictures Credits: Cristiano Loss

References

Loss, C. and B. Davison (2017). "Innovative Composite Steel-Timber Floors with Prefabricated Modular Components." Journal of Engineering Structures 132: 695-713. DOI: 10.1016/j.engstruct.2016.11.062

Composite Steel-Timber Floors: Assembly

Off-side Fabrication

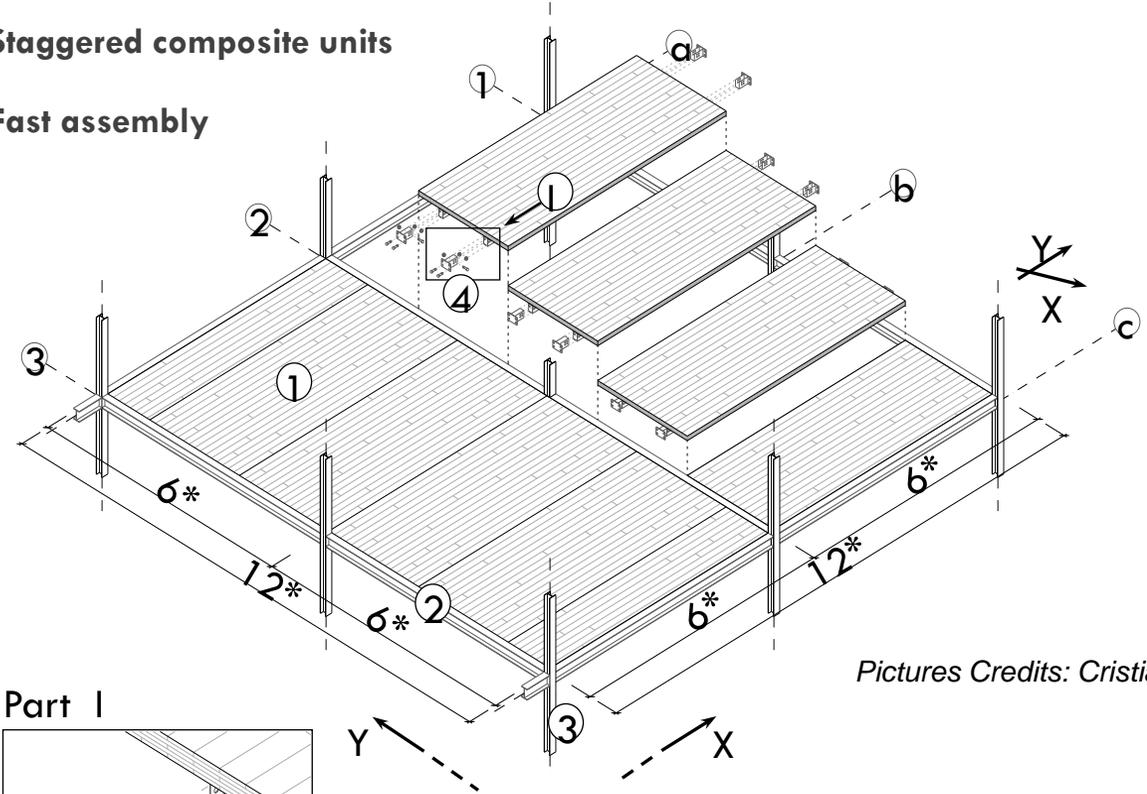


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On-site Installation

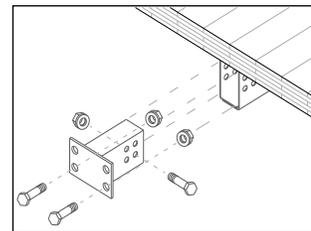
Staggered composite units

Fast assembly



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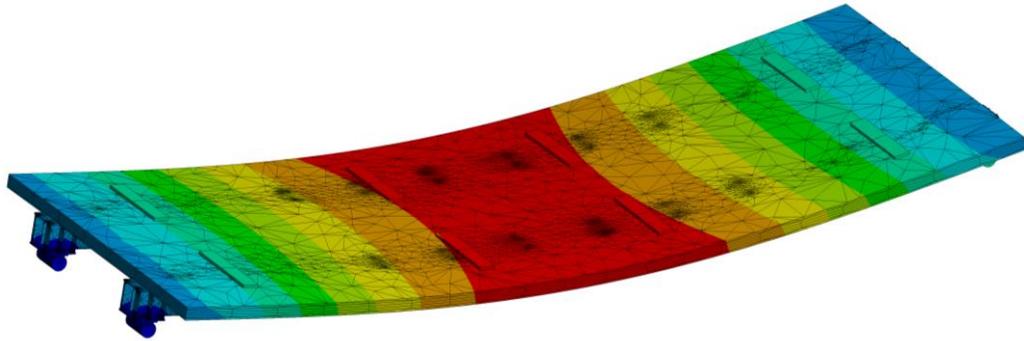
Part I



- ① Composite elements
- ② Columns
- ③ Main beams
- ④ Link joints - bolted

Composite Steel-Timber Floors: Bending Behavior

3D Finite-Element Model

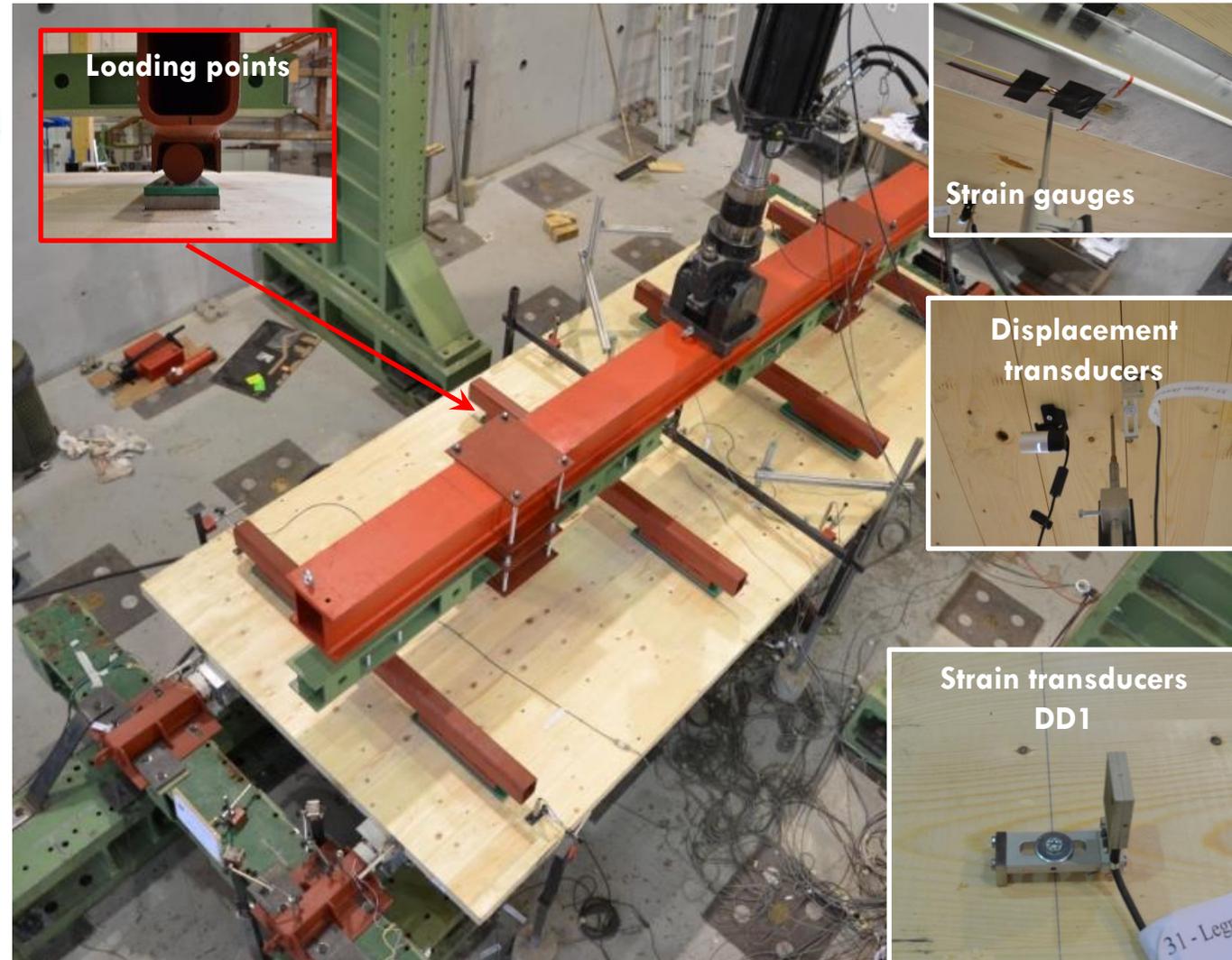


Highlights

- 4 prototypes of composite steel-timber elements
- 12 specimens tested including two testing protocols
- Redundant measurements (46 channels used)
- Multiple points for measuring deflections, slips, strain in wood and steel members

Multi-point bending tests

Pictures Credits: Cristiano Loss

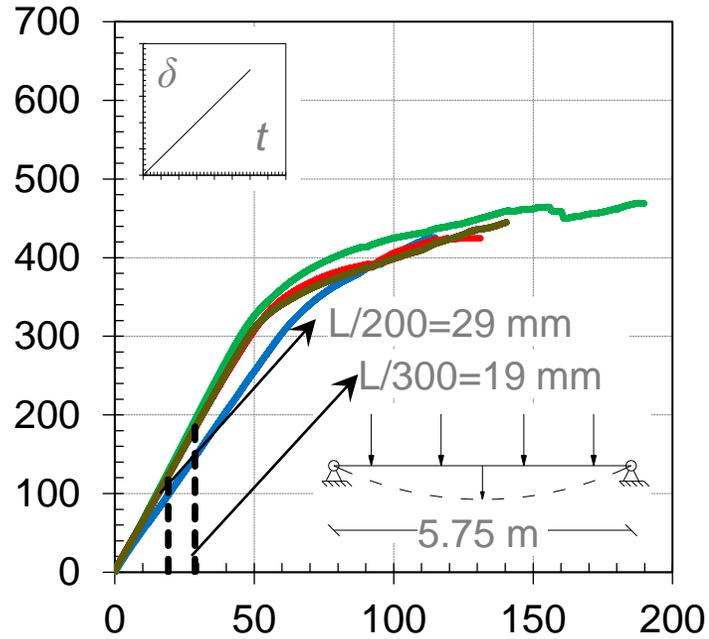


References

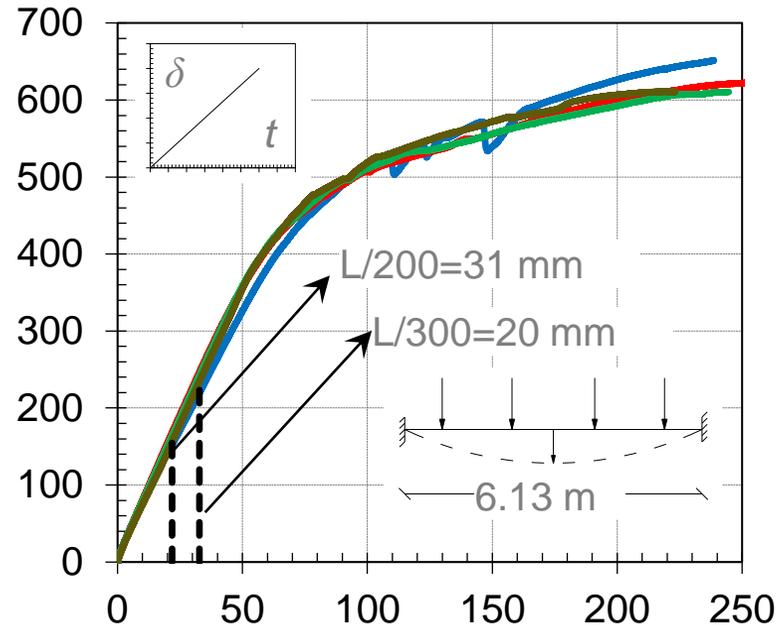
Loss, C. and B. Davison (2017). "Innovative Composite Steel-Timber Floors with Prefabricated Modular Components." *Journal of Engineering Structures* 132: 695-713. DOI: 10.1016/j.engstruct.2016.11.062

Composite Steel-Timber Floors: Bending Behavior - Comparison

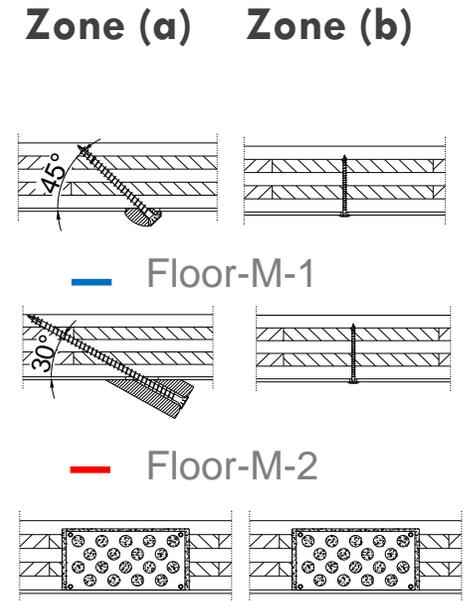
Simple support conditions



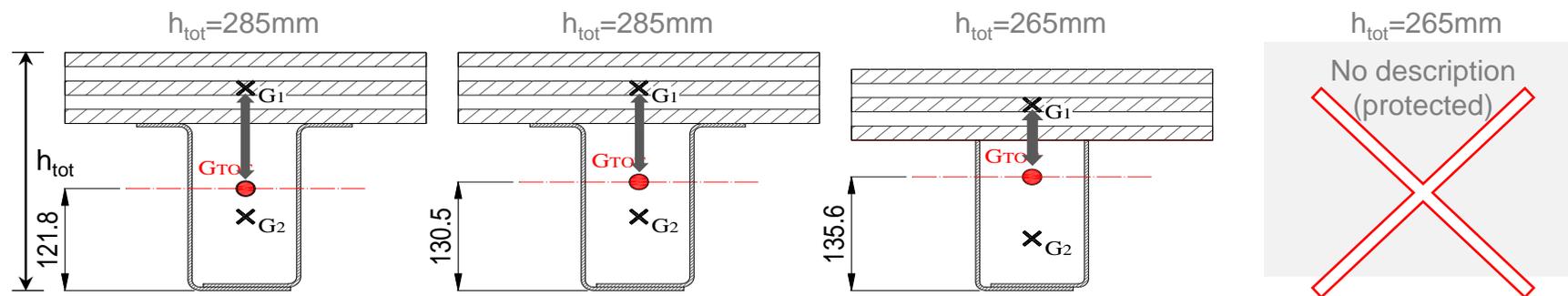
Simulated Restraint conditions



Beam-to-slab connections



Cross-section of the composite floors



- Floor-M-3
- Floor-M-2
- Floor-M-1
- Floor-M-4 (protected)

Pictures Credits: Cristiano Loss

Composite steel-timber floors: Damage Assessment

Damage in the steel beams - Severe



Pictures Credits: Cristiano Loss

Damage in the steel links - Severe



Pictures Credits: Cristiano Loss

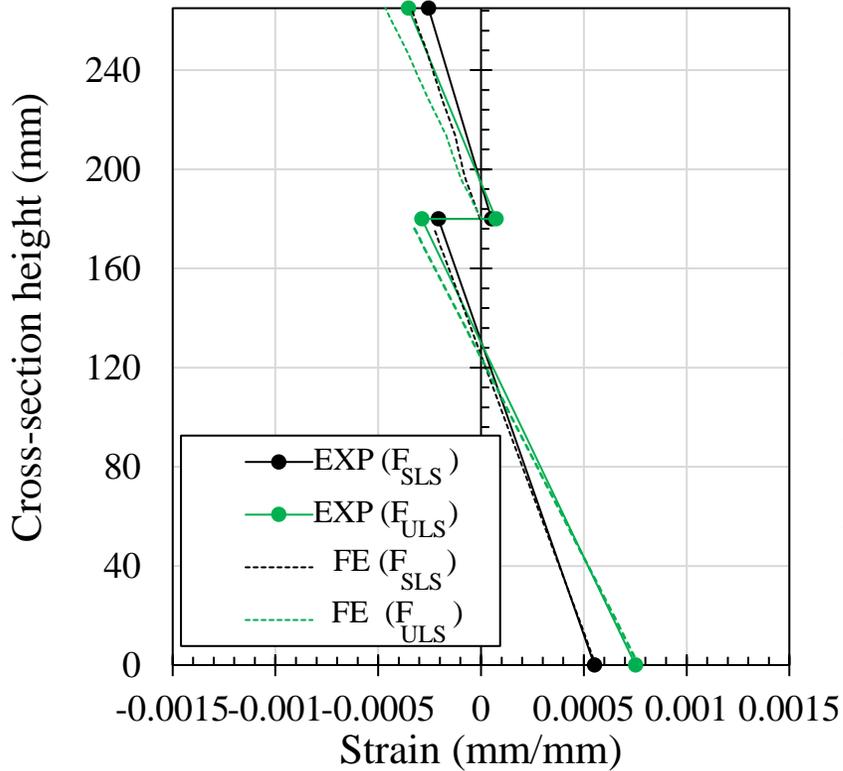
Damage in the STS - Limited



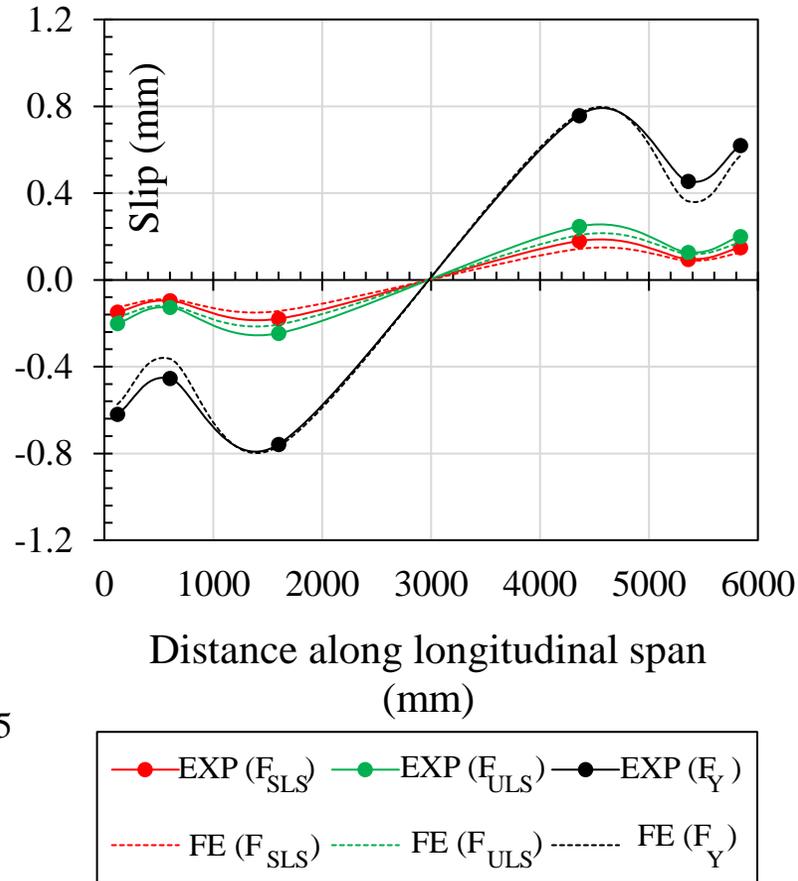
Pictures Credits: Cristiano Loss

Composite Steel-Timber Floors: Bending Behavior – Calibration

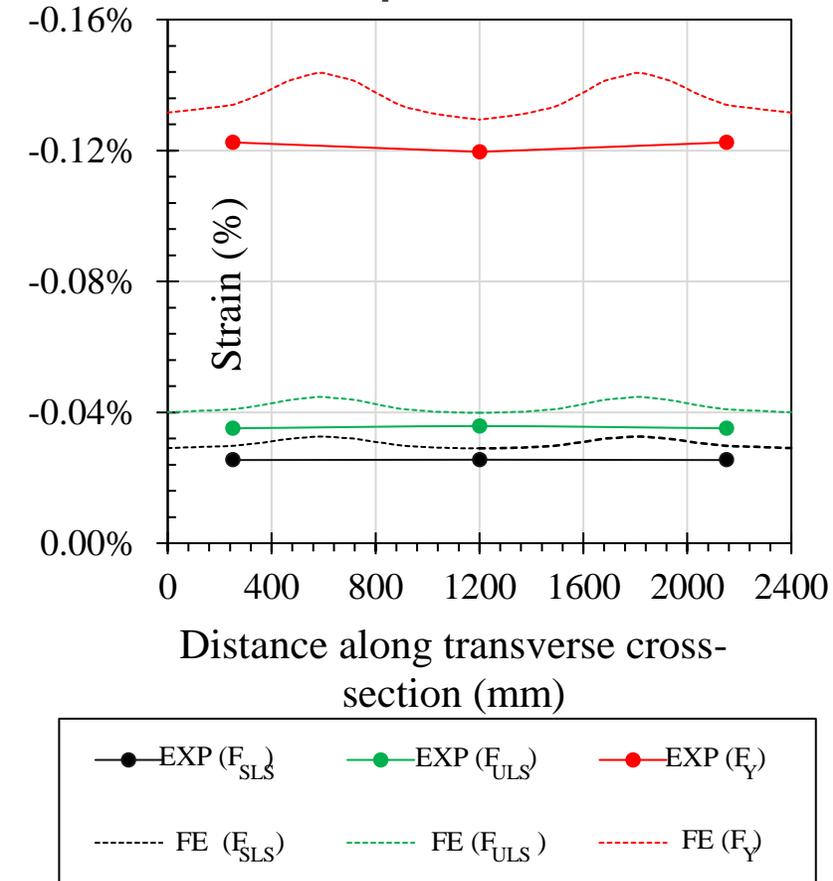
Strain distribution across mid-span cross-section



Beam-to-slab slip along the major axis of the floor



Strain distribution in the transverse direction at mid-span section

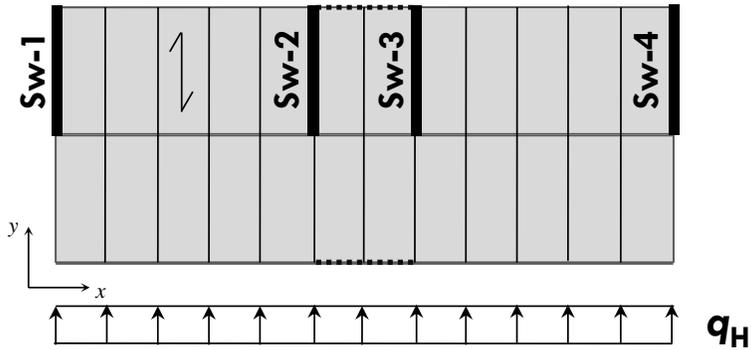


References

Owolabi, D. and C. Loss (2022). "Experimental and Numerical Study on the Bending Response of a Prefabricated Composite CLT-Steel Floor Module." Engineering Structures 260: 114278. DOI: 10.1016/j.engstruct.2022.114278

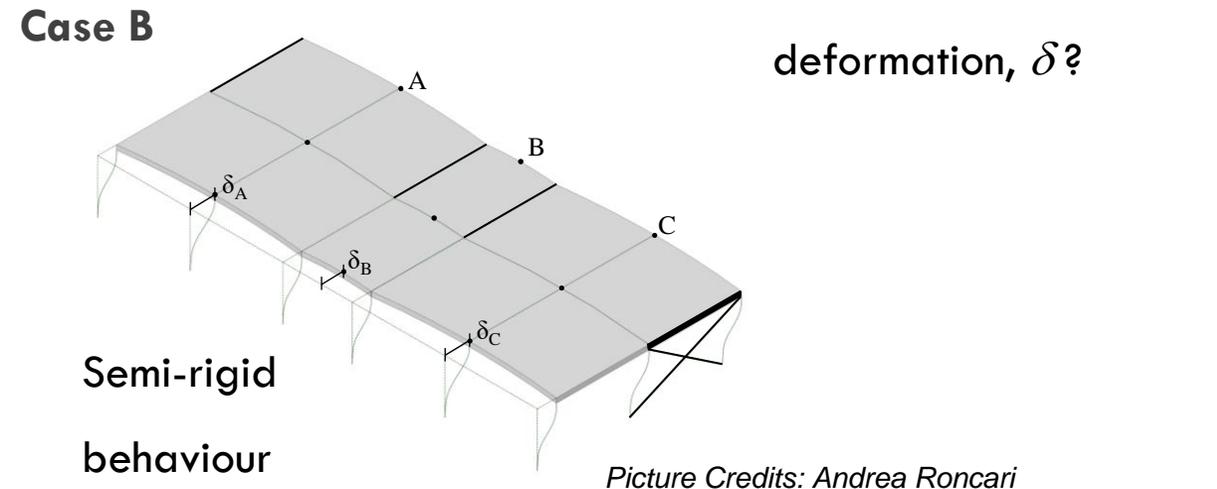
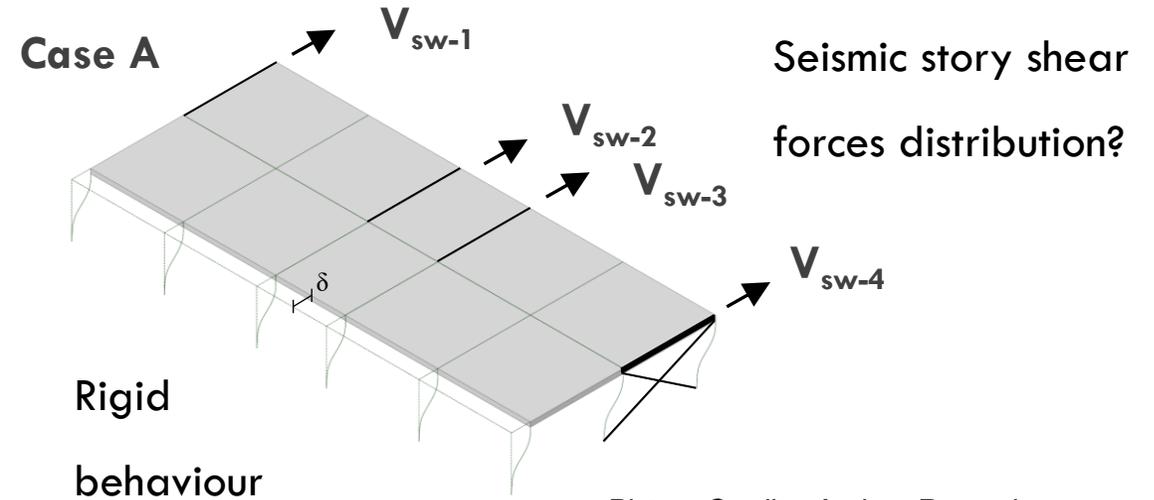
Composite Steel-Timber Diaphragms: General

Design Problem - Schematic



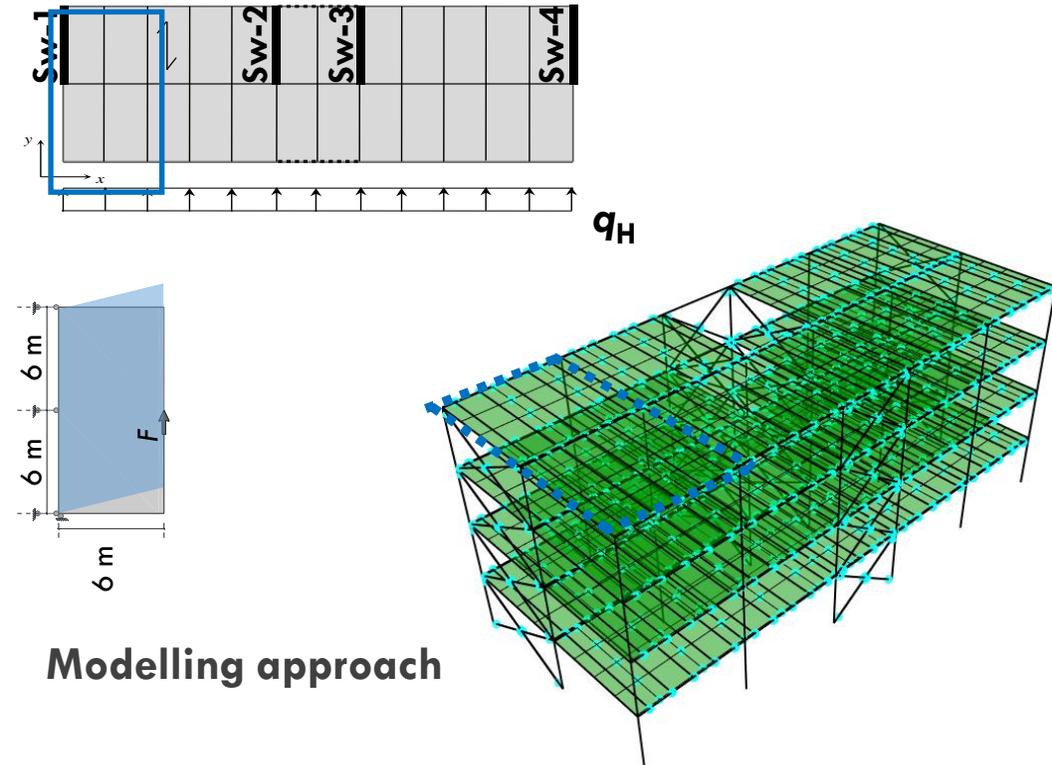
Design Questions:

- How do I design this system and its sub-assembly?
- Could I apply a simplified method of analysis (like equivalent static procedures)?
- How does the diaphragm perform (in-plane loads)?
- How does the flexibility of the diaphragm influence lateral building behavior?



Composite Steel-Timber Diaphragms: In-plane Behavior

3D Finite-Element Model



Modelling approach

- Should include all stiffness properties of members and connections, as well as joints
- Should include P-delta effects and other geometric nonlinearity (use also initial imperfection)

Experimental Tests – Full-Scale System-Level

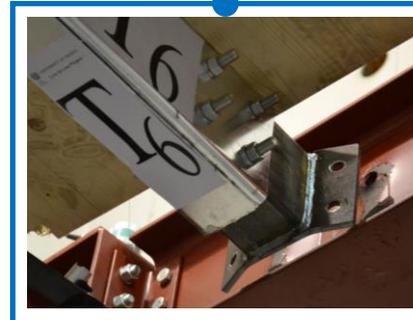


Pictures Credits: Cristiano Loss

References

Loss, C. and A. Frangi (2017). "Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms." Journal of Engineering Structures 138: 229-244. DOI: 10.1016/j.engstruct.2017.02.032

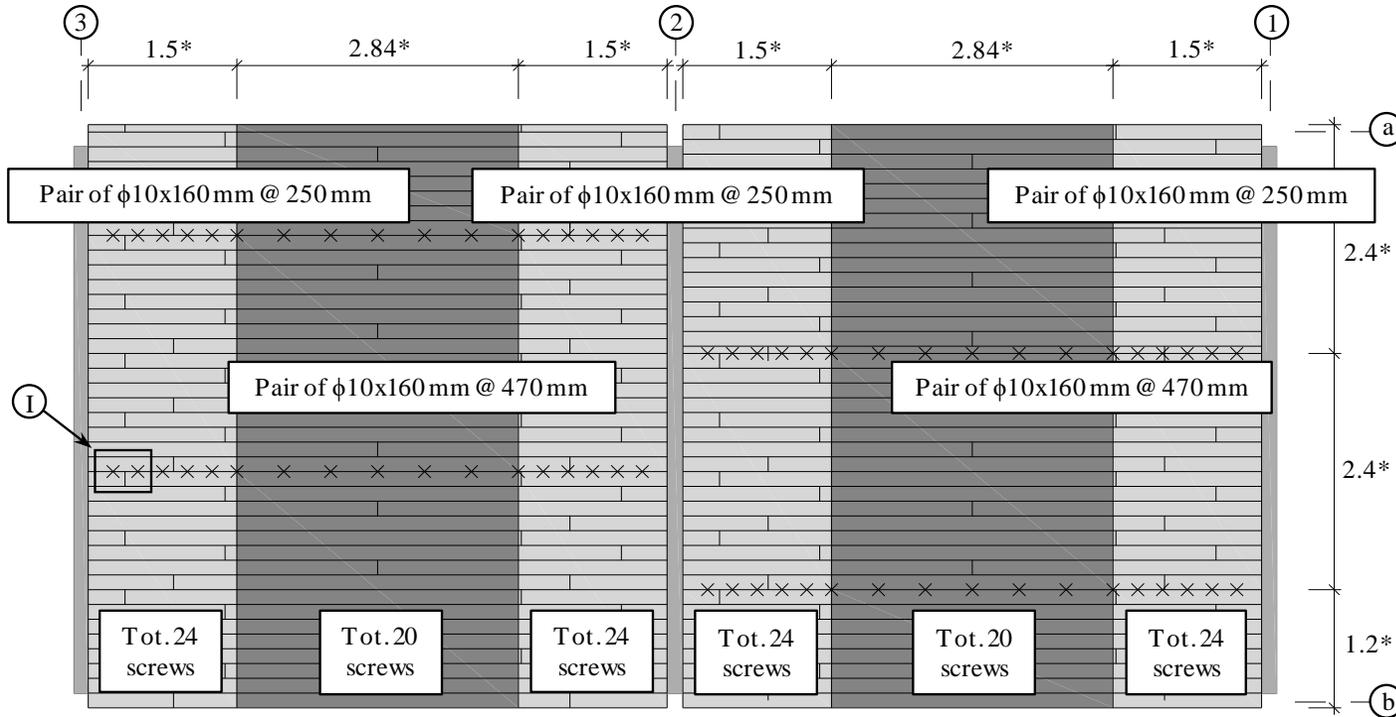
Observed failures



Composite Steel-Timber Diaphragms: In-plane Behavior

Selection of best configuration for the connections in the slab (among CLT panels)

STS arrangement

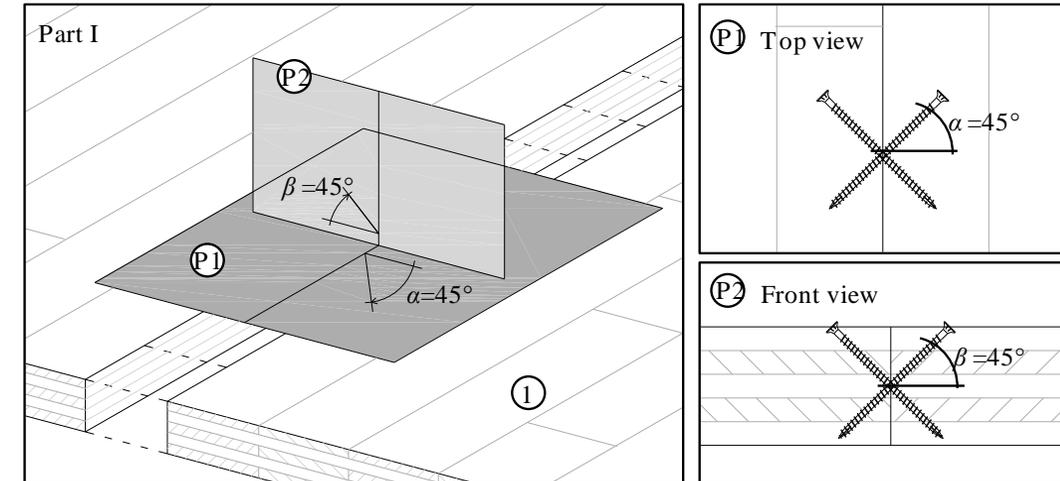


Remarks

Sensitivity analysis has been performed to evaluate impact of connections properties and slab thickness on the in-plane diaphragm stiffness

STS installation

Pictures Credits: Cristiano Loss

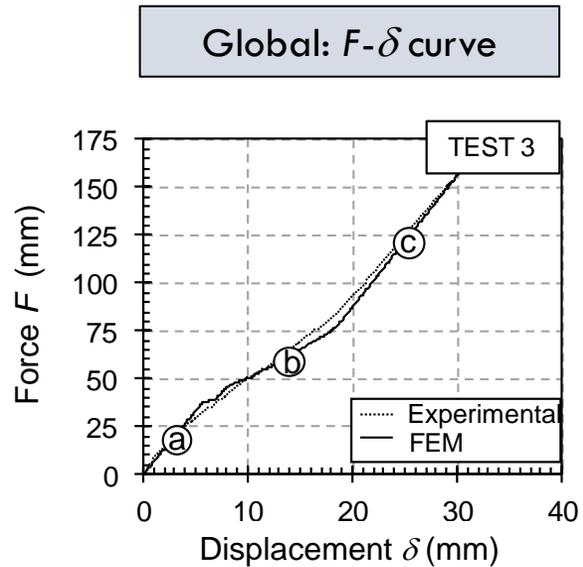


References

Loss, C., S. Rossi and T. Tannert (2018). "In-plane stiffness of hybrid steel-cross-laminated timber floor diaphragms." Journal of Structural Engineering 144(8): 04018128. DOI: 10.1061/%28ASCE%29ST.1943-541X.0002105

Composite Steel-Timber Diaphragms: In-plane Behavior

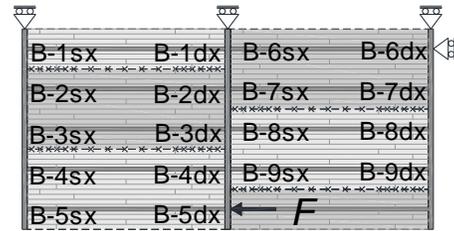
Experimental Method Versus Finite-Element Model Calibration



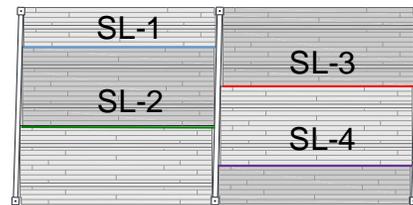
Stiffness [kN/mm]	(a)	(b)	(c)
Experimental	5.34	3.95	6.06
FEM	5.66	3.39	6.88
ϵ [%]	6.1	-14.2	13.6

Nomenclature

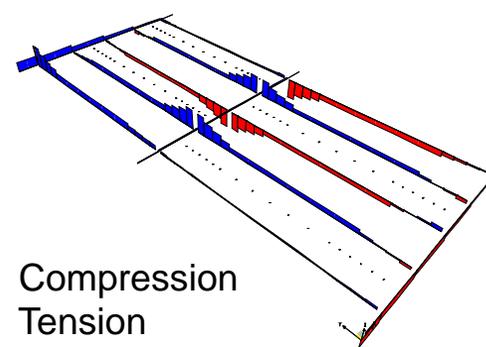
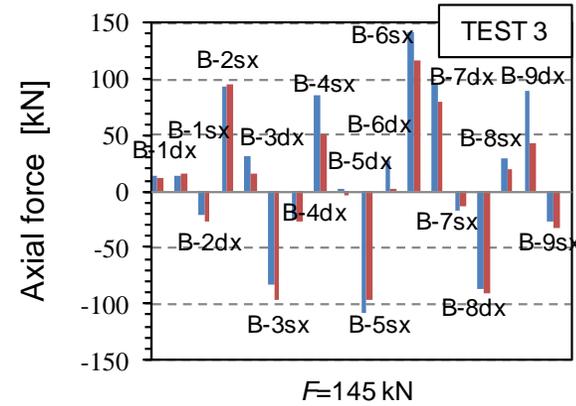
Steel beams



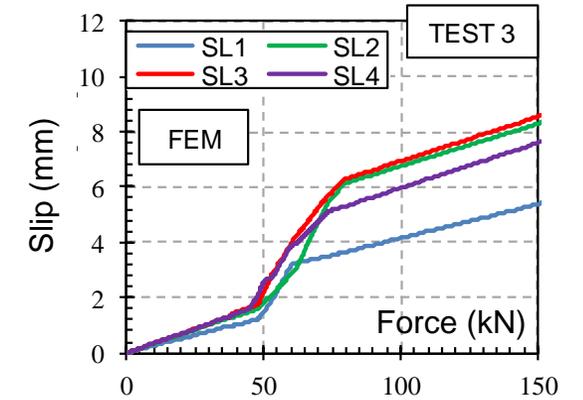
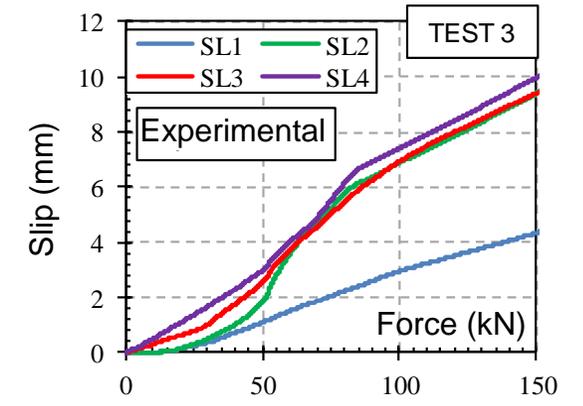
CLT slabs



Local: Beams



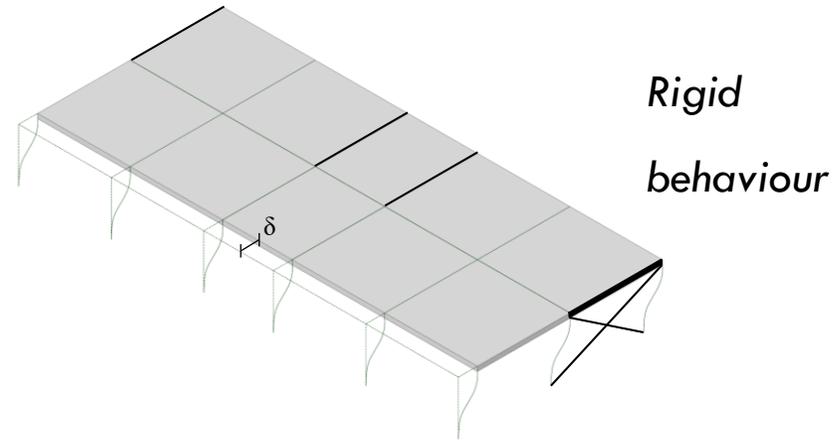
Local: Slab members



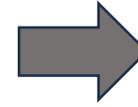
Fine-tuning Modelling Approach

- The Finite-Element Model should be able to capture both global and local response (including stress on members and deformation, whether this referred to elements of connections)

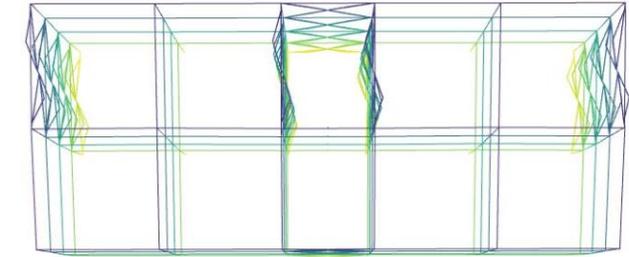
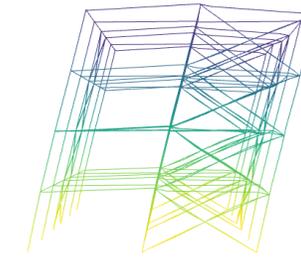
Composite Steel-Timber Diaphragms: Seismic Performance Evaluation



Model I



Mode shape & Fundamental Period (T)

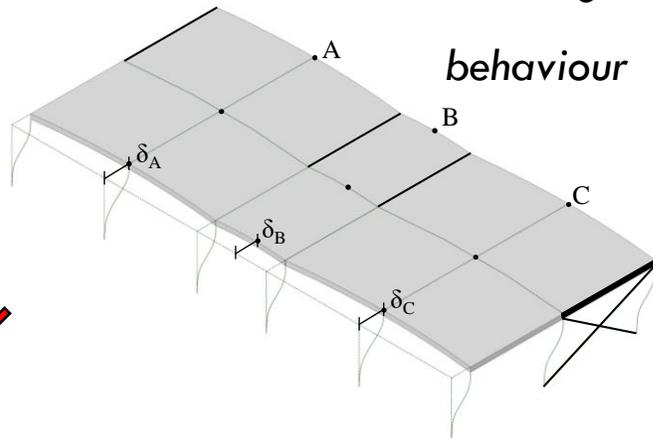


T=0.281s

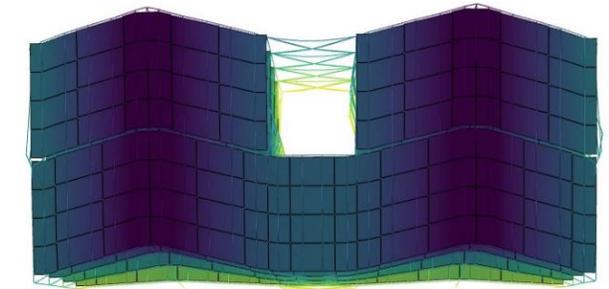
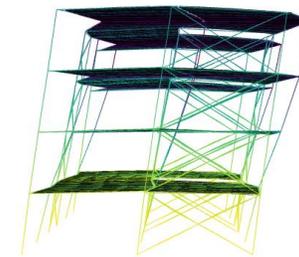
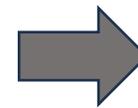


With STS

Semi-rigid behaviour



Model II

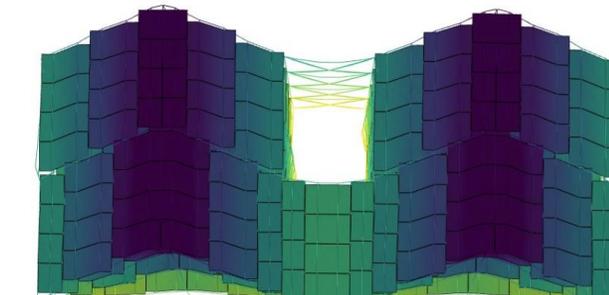
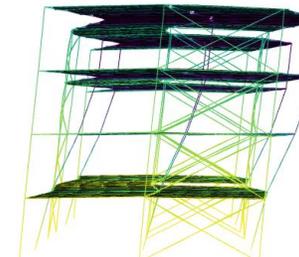
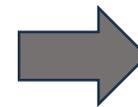


T=0.337s **↑ 20%**



Without STS

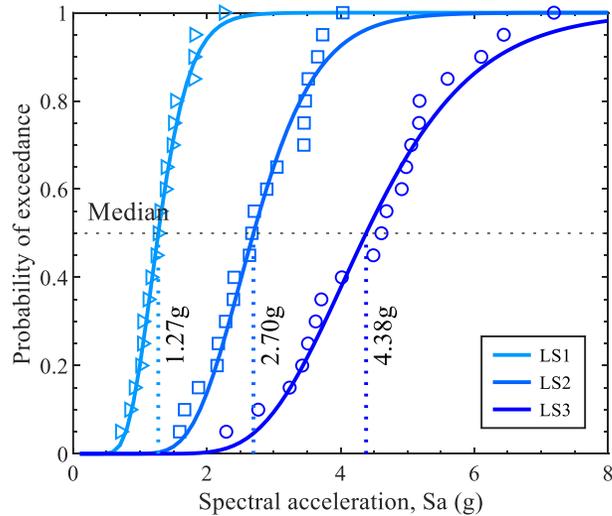
Model III



T=0.389s **↑ 38%**



Composite Steel-Timber Diaphragms: Seismic Performance Evaluation



Model II

Fragility Curves: Definition

$$P(ds \geq DS | IM) = \Phi \left(\frac{\ln(IM) - \mu}{\sigma} \right)$$

Statistics Model	Sa _{16%} (g)			Sa _{50%} (g)			Sa _{84%} (g)			β_{Sa}		
	I	II	III	I	II	III	I	II	III	I	II	III
LS1	0.91	0.95	0.85	1.17	1.27	1.09	1.52	1.70	1.41	0.26	0.29	0.25
LS2	2.21	2.05	1.79	2.75	2.70	2.26	3.41	3.54	2.84	0.22	0.27	0.23
LS3	3.41	3.29	2.53	4.46	4.38	3.50	5.83	5.84	4.83	0.27	0.29	0.33

Where

Limit states	Evaluation criterion	Description
LS1	Yielding point of individual IDA curve	Onset of the first nonlinear behavior of the numerical model, the point deviating the initial IDA tangent
LS2	2% maximum interstory drift ratio	Performance level of collapse prevention for braced steel frames (ASCE 41-17 S2, FEMA 356 Table C1-3)
LS3	Global collapse	Simulated collapse point represented by the flattening of individual IDA curve or the last converged point

Readings

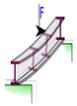
- **LS1:** 16% of records need to reach $Sa \geq 0.95$ g, 50% records need to reach $Sa \geq 1.27$ g, and 84% records need to reach $Sa \geq 1.70$ g

References

Zhang, C. and C. Loss (2023). "Evaluation of Seismic Fragilities of Special Concentrically Braced Frame Hybrid Buildings Equipped with Prefabricated Cross-Laminated Timber-Steel Composite Floor Diaphragms." Bulletin of Earthquake Engineering 21: 6423-6452. URL: <https://doi.org/10.1007/s10518-023-01770-3>

Composite Steel-Timber Floors: Design for Serviceability Requirements

Vibration control: Design for Vibration



specifying minimum stiffness

f

Stipulation of a minimum natural frequency

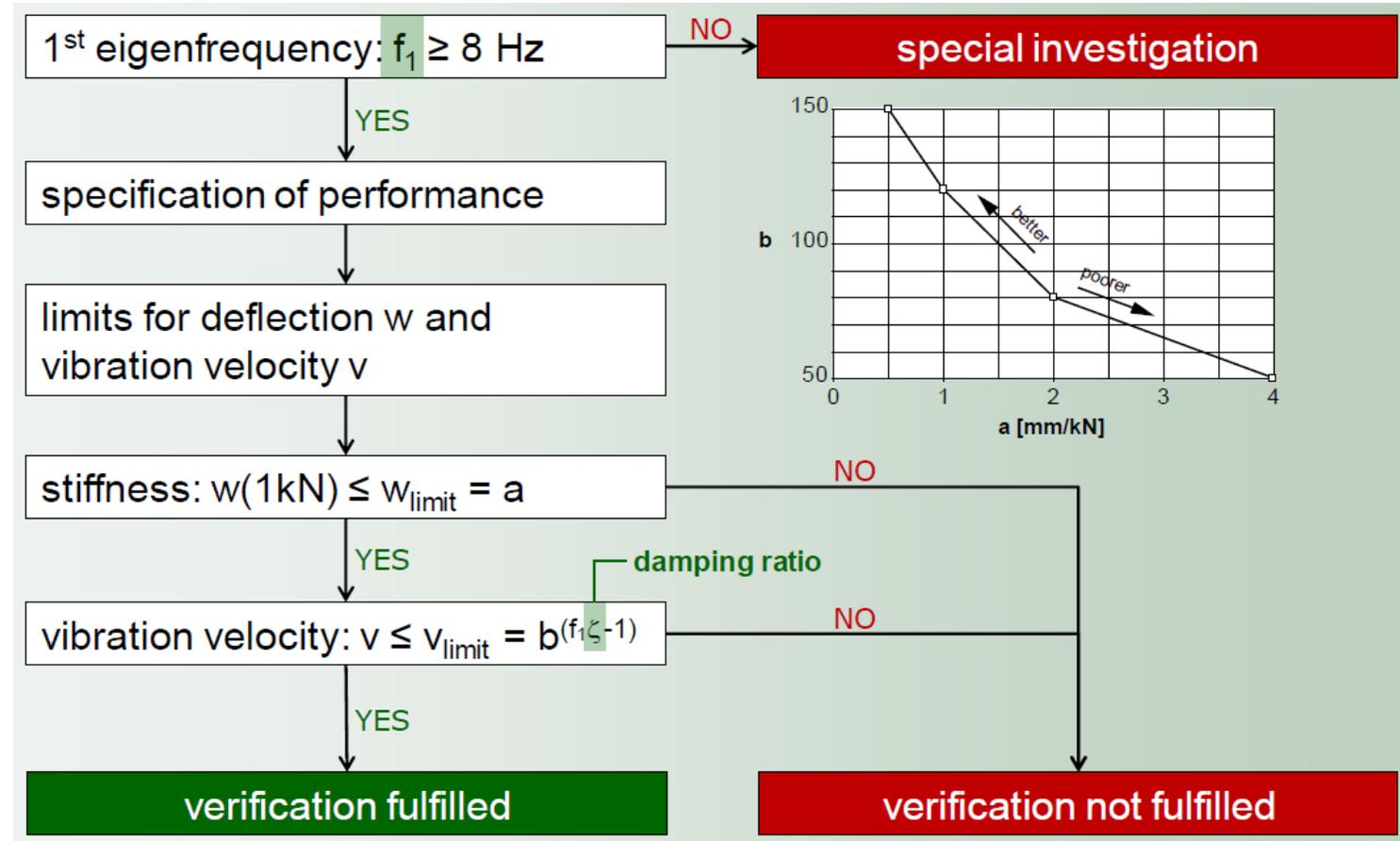


Capping the dynamic response of a floor (i.e., acceleration, velocity)

Highlights

- Limiting parameters and velocity have been calibrated for all-wood floors only
- Uncertainty on the damping value for steel-timber flooring systems

Design in accordance with Eurocode 5 – EN 1995-1-1



Picture Credits: Gerhard Schickhofer

Composite Steel-Timber Floors: Vibration Performance - Ongoing

Experimental Campaign



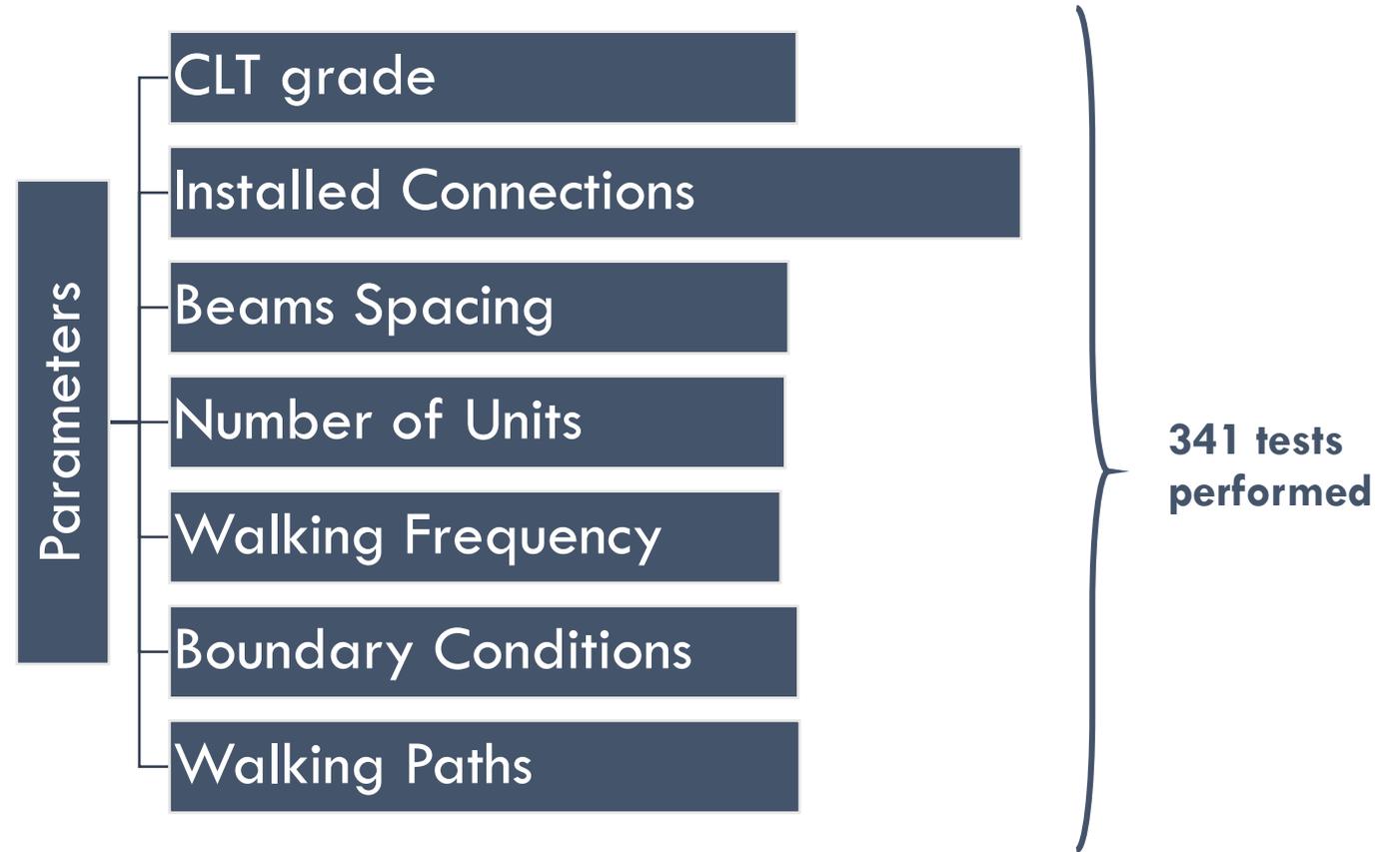
Walking-induced acceleration measurement
(ISO 10137 & BS EN 16929)



Subjective vibration performance assessment
(ISO/TR 21136 (ISO 2017))

Pictures Credits: David Owolabi

Experimental Matrix



References

Owolabi, D., C. Loss and J. Zhou (2023). "Vibration Properties and Serviceability Performance of a Modular Cross-laminated timber-Steel Composite Floor System." *Journal of Structural Engineering (ASCE)*, 149(12): 04023171. URL: <https://doi.org/10.1061/JSENDH.STENG-12587>

Aloisio, A., D. Pasca, D. Owolabi and C. Loss (2024). "Vibration serviceability of hybrid CLT-steel composite floors based on experimental and numerical investigations using random walk models." *Engineering Structures* 304: 117600. URL: <https://doi.org/10.1016/j.engstruct.2024.117600>

FIRST CASE STUDY BUILDING (completed in 2018)

Shipment (Logistic)



Photo credits IAMEC S.R.L

Lifting and installation of units



Photo credits IAMEC S.R.L

Completion of one floor



Photo credits IAMEC S.R.L

Thank You

Dr. Cristiano Loss

✉ Cristiano.loss@ubc.ca

