Effect of Construction Features on the Dynamic Performance of Mid-Rise CLT Platform-Type Buildings

Forum Wood Building Nordic (WBN)
MORE -Mobilizing Our Resources Efficiently

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Outline

- Introduction
- CLT as an alternative construction material
- Reference Building
- FE Numerical Models
- Parametric studies

Introduction

- Land use policies for European and other cities have become a major challenge due to:
  - ❖ rural-to-urban migration fuelled population growth
- Thus, mid- and high-rise construction strategies are being employed to meet occupancy demands

Introduction

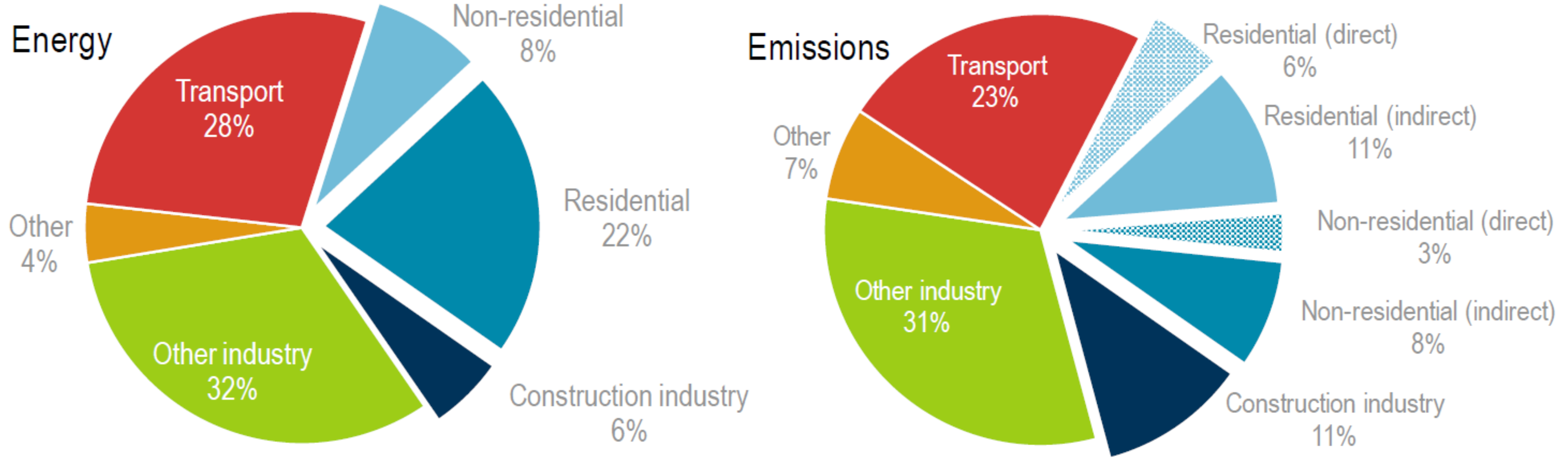
- However, it is reported that building construction materials account for around **40%** of all global primary energy consumption and Greenhouse Gas emissions

Introduction

Energy and emissions in the buildings and construction sector

Building construction and operations accounted for the largest share of both global final energy use (36%) and energy-related CO_2 emissions (39%) in 2018 (Figure 2).

Figure 2 • Global share of buildings and construction final energy and emissions, 2018

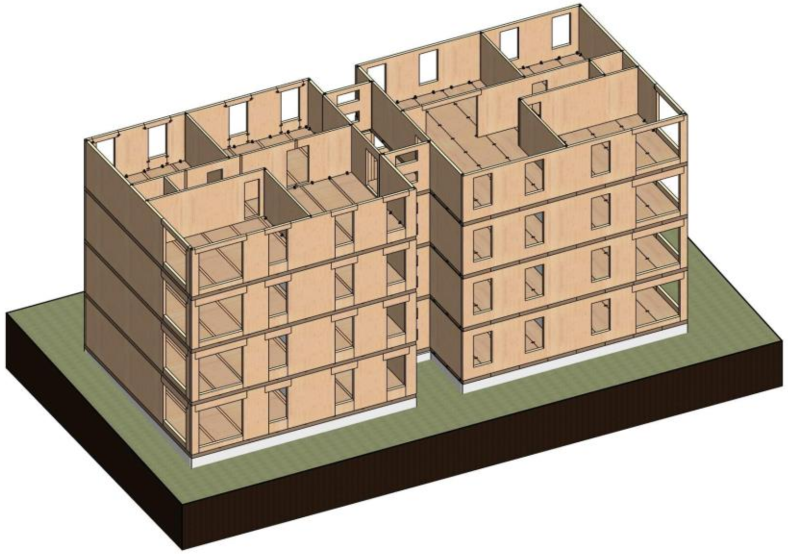


Notes: *Construction industry* is the portion (estimated) of overall industry devoted to manufacturing building construction materials such as steel, cement and glass. Indirect emissions are emissions from power generation for electricity and commercial heat.

Sources: Adapted from IEA (2019a), *World Energy Statistics and Balances* (database), www.iea.org/statistics and IEA (2019b), *Energy Technology Perspectives*, buildings model, www.iea.org/buildings.

CLT an Alternative Construction Material

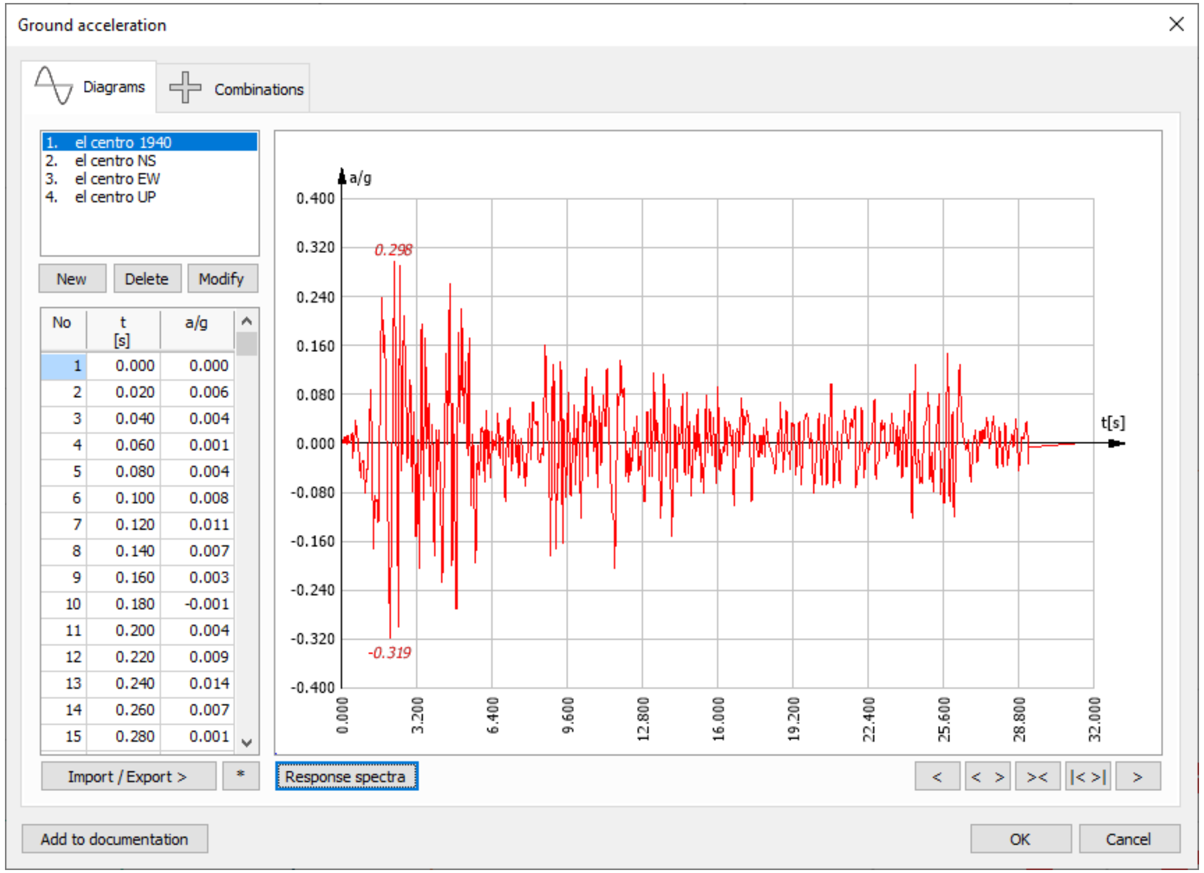
- **CLT** as a structural construction material provides a lot of benefits including:
  - ❖ reduction in total superstructure gravitational weights
  - ❖ reduction in gravitational weight can simplify and speed up construction processes
  - ❖ results in relatively less expensive foundation costs.
  - ❖ being made from wood, CLT has desirable 'green' credentials like renewability of forest resources and carbon sequestration for the lifespans of buildings.



CLT platform-type building

CLT an Alternative Construction Material

- However, like other lightweight structural systems, CLT buildings can be susceptible to high-amplitude motions during ambient or other dynamic force and displacement disturbances



Objectives and Approach

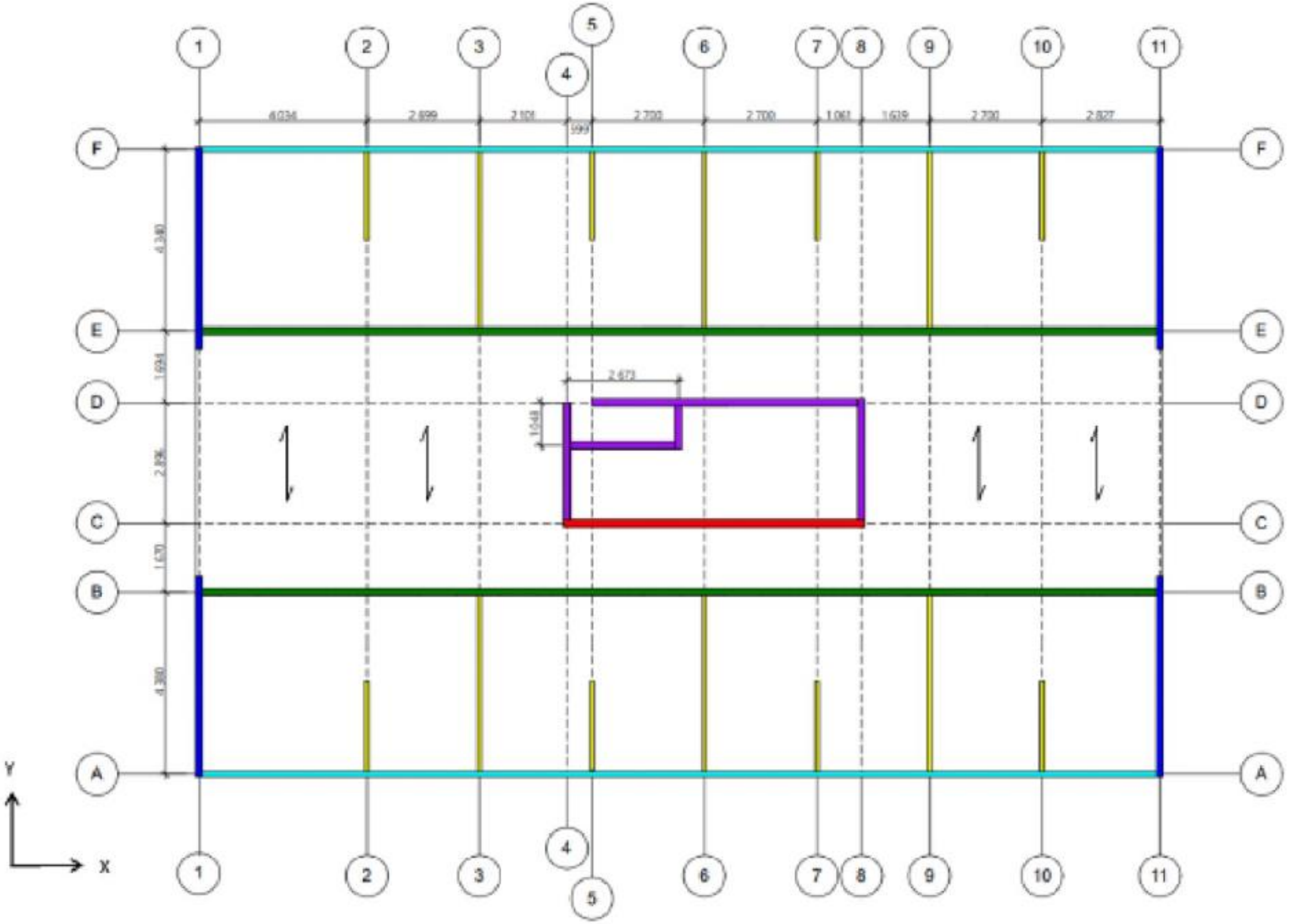
- The study addresses the dynamic behaviour of mid-rise multi-storey buildings constructed from massive CLT elements, with the **objectives** of:
  - ❖ Predicting lateral modal response characteristics of such buildings
  - ❖ Assess the effect of construction variables on the modal characteristics of CLT buildings

- The **approach** involves:
  - ❖ Employing detailed Finite Element (FE) models as a vehicle to meet the objectives
  - ❖ FE models verified with field investigations of ambient dynamic motions of completed CLT buildings
  - ❖ Verified models applied for parametric studies of construction variables

Reference Building

- The 8-storey case-study building is one of the two identical student residence buildings on the campus of the Norwegian University of Life Sciences (NMBU) in Ås

(a) Photograph of reference building



(b) Typical floor plan of the reference building

Reference Building

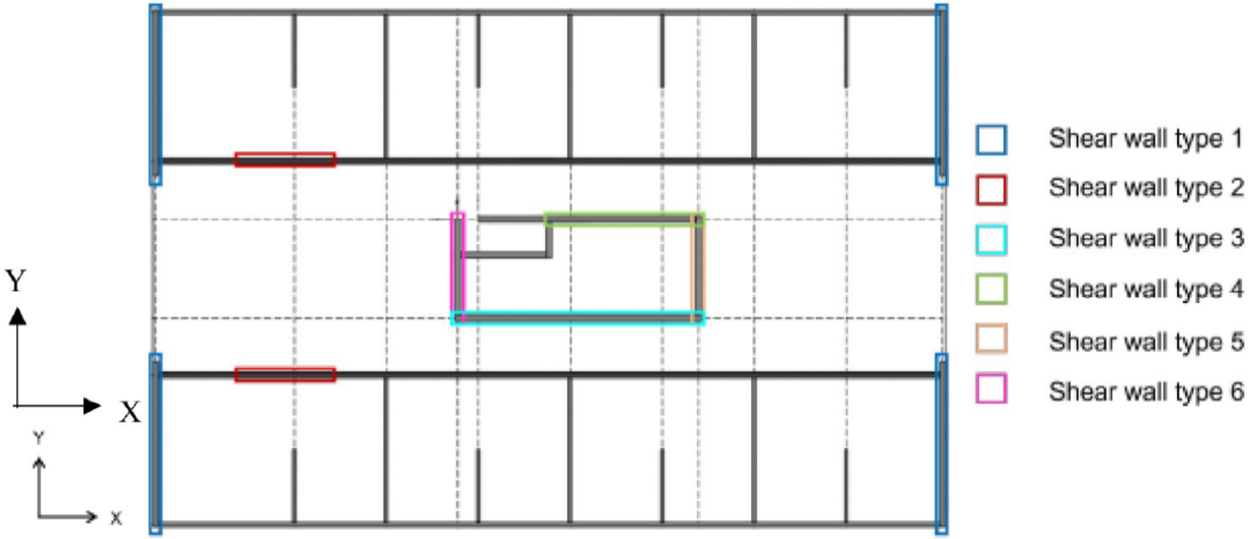


Figure 2. Typical layout of shear walls in reference building.

*AB symbolizes angle bracket.
**HD symbolizes hold-down.

Table 1. Specifications of shear walls and connectors. (Table view)

Shear-wall type	Floor	*AB-type	**HD-type	Shear-wall type	Floor	AB-type	HD-type
1	1–4	AB-7	HD-3	4	1–3	AB-5	HD-1
	5–6	AB-6	HD-2		4–7	AB-1	HD-1
	7–8	AB-6	HD-1		8	AB-1	–
	9	AB-2	HD-1		9	–	–
2	1–8	–	HD-1				
	9	–	–	5 and 6	1–2	AB-5	HD-2
3	1–5	AB-9	HD-3		3–4	AB-4	HD-2
	6	AB-9	HD-2		5–6	AB-4	HD-1
	7–8	AB-8	HD-1		7–8	AB-1	HD-1
	9	AB-3	HD-1		9	–	–

FE Numerical Models

- Numerical models → SAP2000
- Python scripts are developed to carry out
  - ❖ model updating studies
  - ❖ calibration of model
  - ❖ Parameter sensitivity studies
- CLT elements are simulated as 4-node orthotropic thin plates with orthogonal axes of material symmetry (1, 2, 3) coincident with length, width and thickness directions of elements (x, y, and z)
- Small deflections elastic responses are assumed valid

- Wall-to-wall, wall-to-slab and wall-to-foundation connections were simulated as hinges (i.e. having the ability to transfer in-plane force flows but not the ability to transfer bending moments)

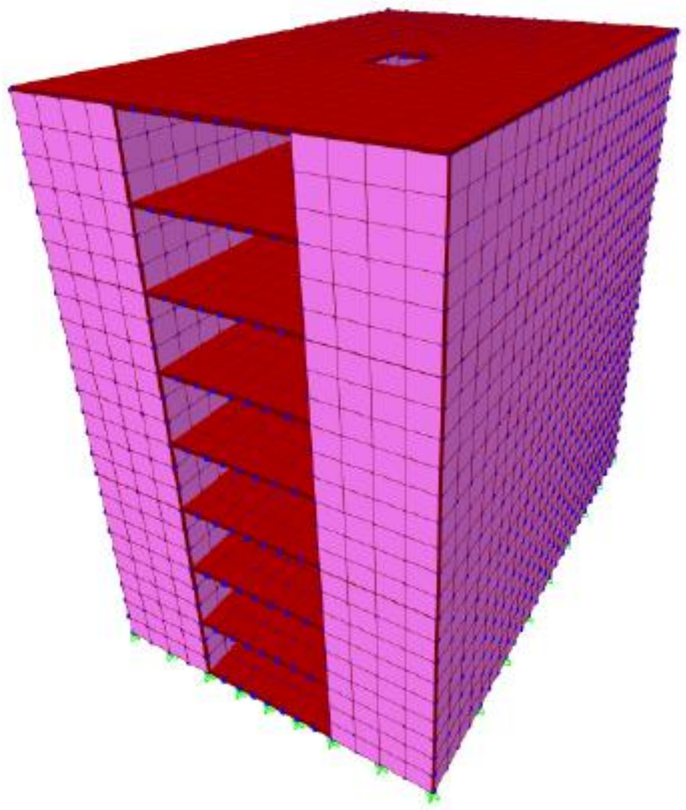


Figure 3. Baseline FE superstructure model.

FE Numerical Models

Table 3. Reference (seed) properties for CLT elements*

CLT-Panel Layup [mm]	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_1 [GPa]	G_2 [GPa]	G_3 [GPa]
CLT 90 3S (30-30-30)	7.46	3.91	0.30	0.37	0.04	0.04
CLT 100 5S (20-20-20-20-20)	6.75	4.62	0.30	0.34	0.03	0.03
CLT 120 5S (30-20-20-20-30)	7.46	3.91	0.30	0.37	0.04	0.04
CLT 130 5S (30-20-30-20-30)	7.73	3.64	0.30	0.39	0.04	0.04
CLT 140 5S (40-20-20-20-40)	7.96	3.41	0.30	0.40	0.04	0.04
CLT 160 5S (40-20-40-20-40)	8.34	3.03	0.30	0.42	0.04	0.04
CLT 180 5S (40-30-40-30-40)	7.46	3.91	0.30	0.37	0.04	0.04
CLT 200 5S (40-40-40-40-40)	6.75	4.62	0.30	0.34	0.03	0.03

**Parallel to face laminations (direction-1); perpendicular to face laminations (direction-2); direction-3 is perpendicular to plate.*

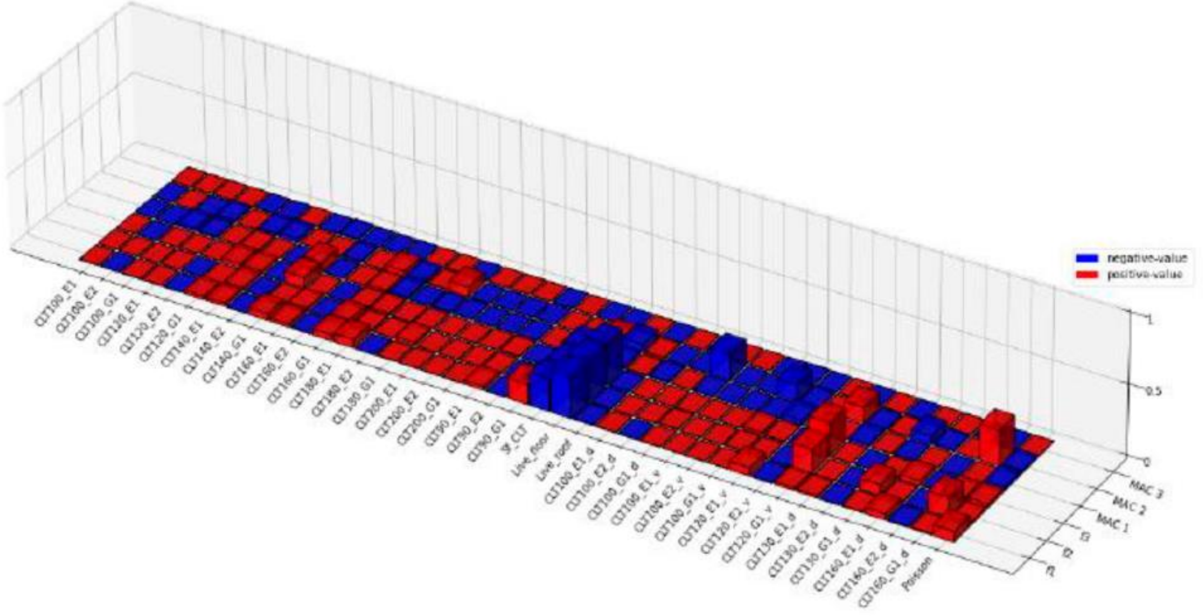
FE Numerical Models

- Sensitivity analyses assessment based on:
  - ❖ stiffness properties of CLT elements
  - ❖ superimposed dead and live loads on elevated floors

$$[S] = \frac{\partial R}{\partial P} \qquad (5)$$

If the sensitivity matrix [S] is evaluated for M parameters in relation to N different responses, then [S] is N by M in dimension,

$$[S] = \begin{bmatrix} \frac{\partial R_1}{\partial P_1} & \frac{\partial R_1}{\partial P_2} & \cdots & \frac{\partial R_1}{\partial P_M} \\ \frac{\partial R_2}{\partial P_1} & \ddots & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \frac{\partial R_N}{\partial P_1} & \cdots & \cdots & \frac{\partial R_N}{\partial P_M} \end{bmatrix} \qquad (6)$$



Parameters with a sum lower than 10^{-7} are deemed insensitive

FE Numerical Models

- Performance of the updated model was evaluated using a cost function implementing both;
  - ❖ Modal Assurance Criteria (MAC) and an
  - ❖ Eigenfrequency Deviation Criterion (f_{dev}),

$$C = \frac{1}{n}\sum_{x=1}^{n}\left(\frac{|f_{e,x} - f_{a,x}|}{f_{e,x}} + (1 - MAC_x)\right)$$

Where

$$\frac{1}{n}\sum_{x=1}^{n}\left(\frac{|f_{e,x} - f_{a,x}|}{f_{e,x}}\right) = f_{dev}$$

❑ ***Leading to Numerical model verification***

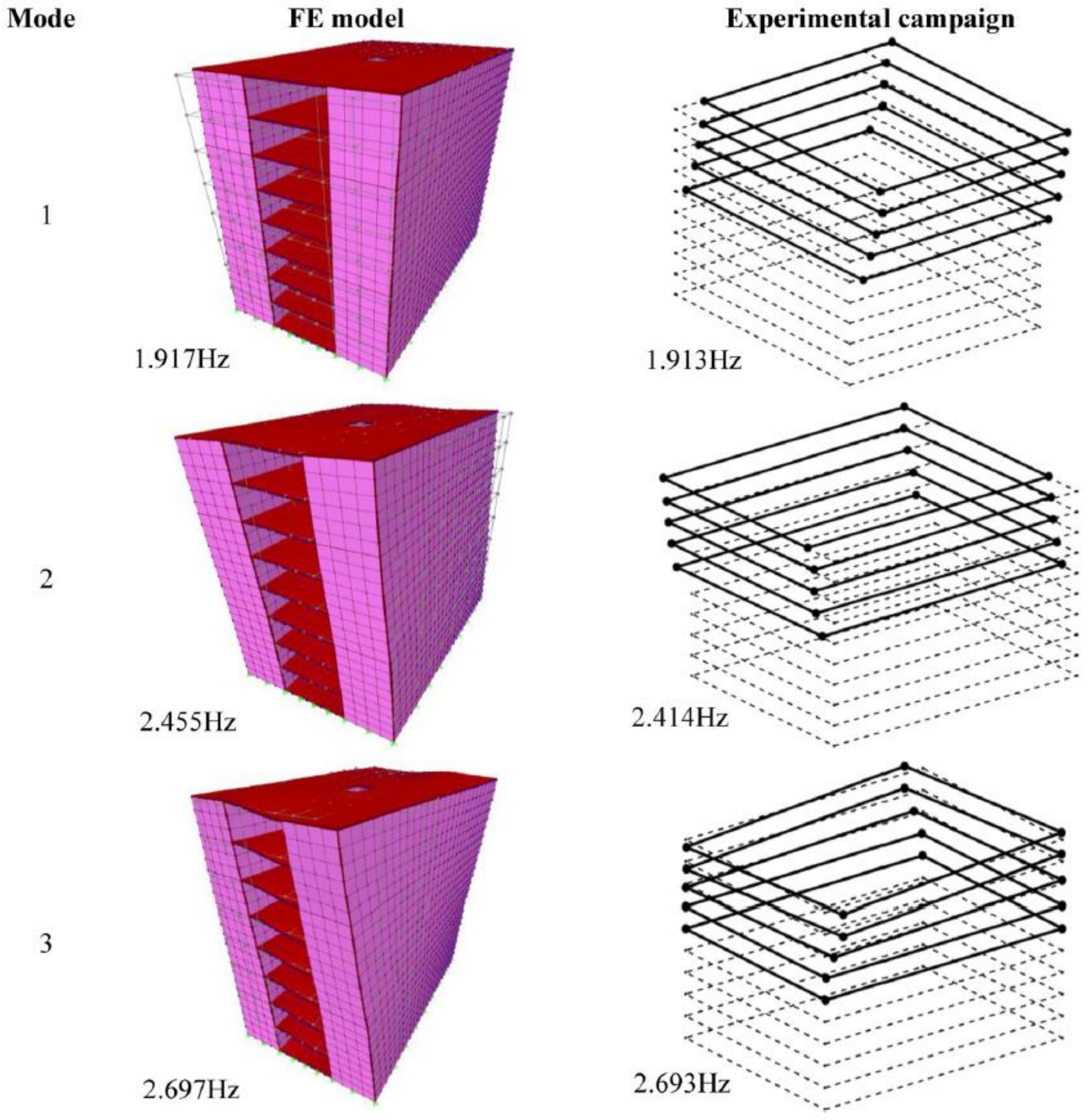
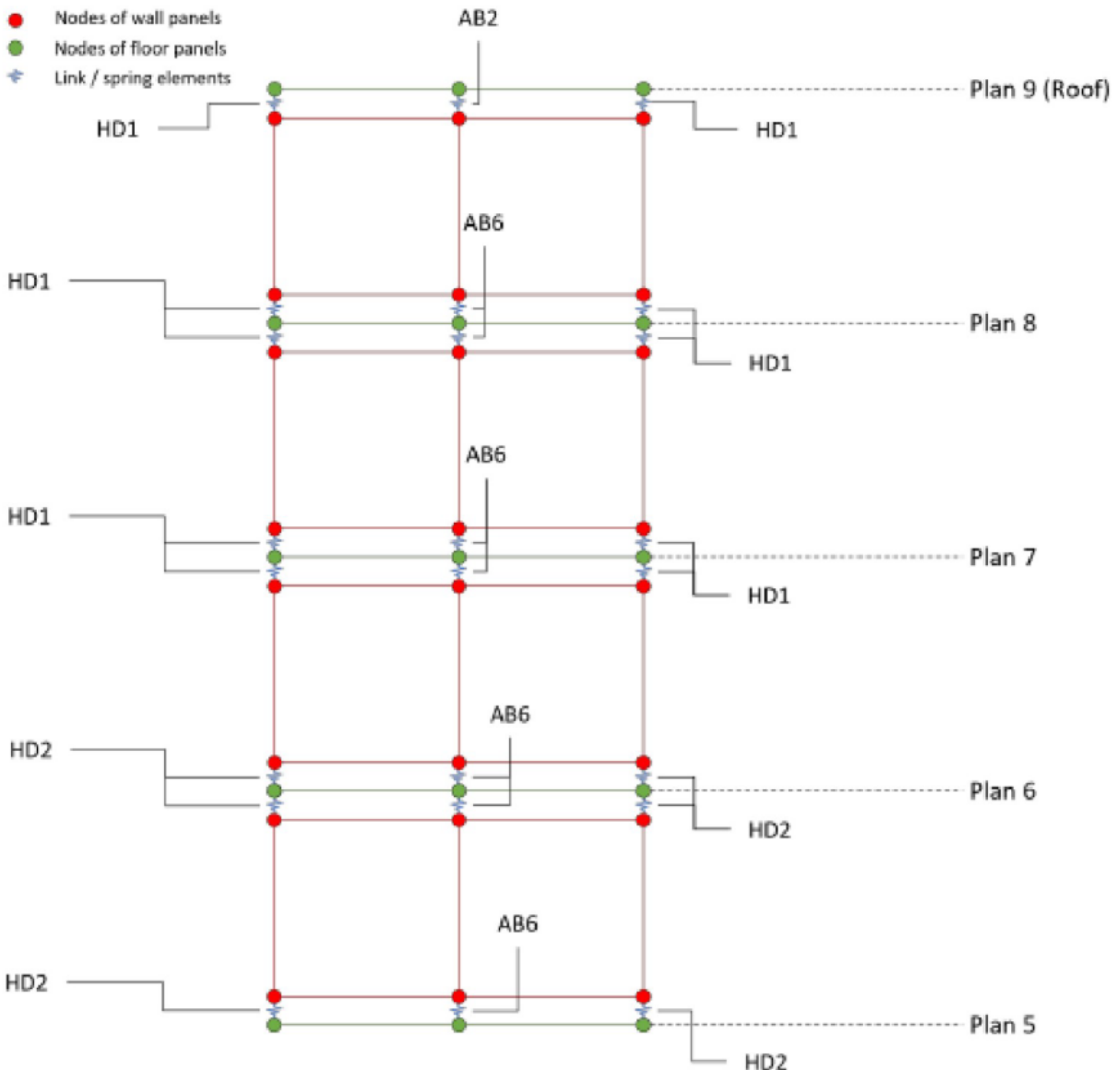


Figure 4. FE model versus experimental mode shapes

Effect of Connector Elements

- The shear wall connectors are modeled as zero-length linear springs (assigned with 6-DOF stiffnesses in 3-D space)
- The procedure of applying the link elements is as shown schematically
- The nodes of wall and slab panels are adjusted so that they no longer coincide, with an added thickness of half of the slab thickness between them
- Furthermore, the slab nodes and wall nodes are connected with the link elements, based on experimental connector stiffness values



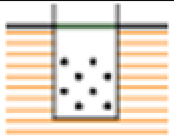
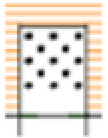
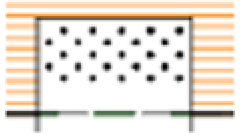
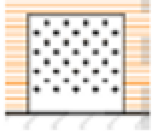
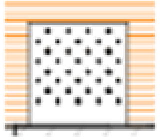
Effect of Connector Elements

Table 7. Stiffness of angle bracket and hold-down anchors in FE analyses. (Table view)

Type of hold-down	Number of brackets	Tensile stiffness (kN/mm)
HD-1	1	2.65
HD-2	2	5.30
HD-3	3	7.95
HD-4	4	10.6
HD-5	5	13.3

- Reference stiffnesses are based on based on experimental studies

$$K_a = n_a \frac{K_{exp}}{n_{exp}}$$

Connector type	Number of nails	Tensile stiffness [KN/mm]	Shear stiffness [KN/mm]	Illustration
AB-2	8	2.98	1.10	
AB-4	13	4.85	1.79	
AB-6	25	9.31	3.44	
AB-8	36	13.41	4.95	
AB-9	36 X 2	26.82	9.90	

Effect of Connector Elements

Table 7. Stiffness of angle bracket and hold-down anchors in FE analyses. (Table view)

Type of hold-down	Number of brackets	Tensile stiffness (kN/mm)
HD-1	1	2.65
HD-2	2	5.30
HD-3	3	7.95
HD-4	4	10.6
HD-5	5	13.3

Table 8. Overview of the types of angle brackets employed in the FE analyses. (Table view)

Connector type	Number of nails	Tensile stiffness (KN/mm)	Shear stiffness (KN/mm)	Illustration
AB-1	5	1.86	0.69	
AB-2	8	2.98	1.10	
AB-3	12	4.47	1.65	
AB-4	13	4.85	1.79	
AB-5	18	6.71	2.48	
AB-6	25	9.31	3.44	
AB-7	35	13.04	4.81	
AB-8	36	13.41	4.95	

Effect of Connector Elements

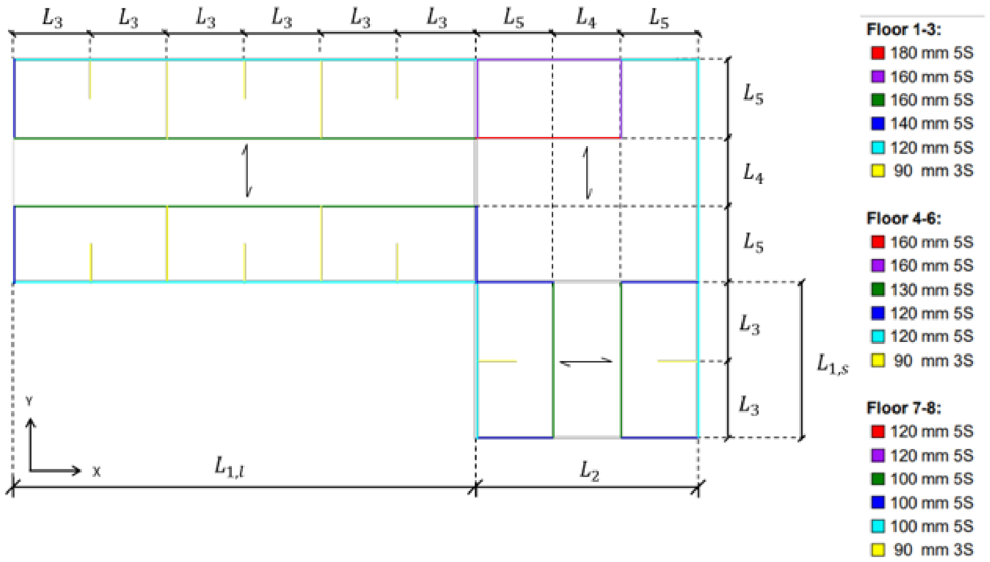
- Based on further sensitivity analyses and model updating, discrepancies between experimental and numerical natural frequencies are observed to have improved significantly

Table 6. FE models versus experimental natural frequencies

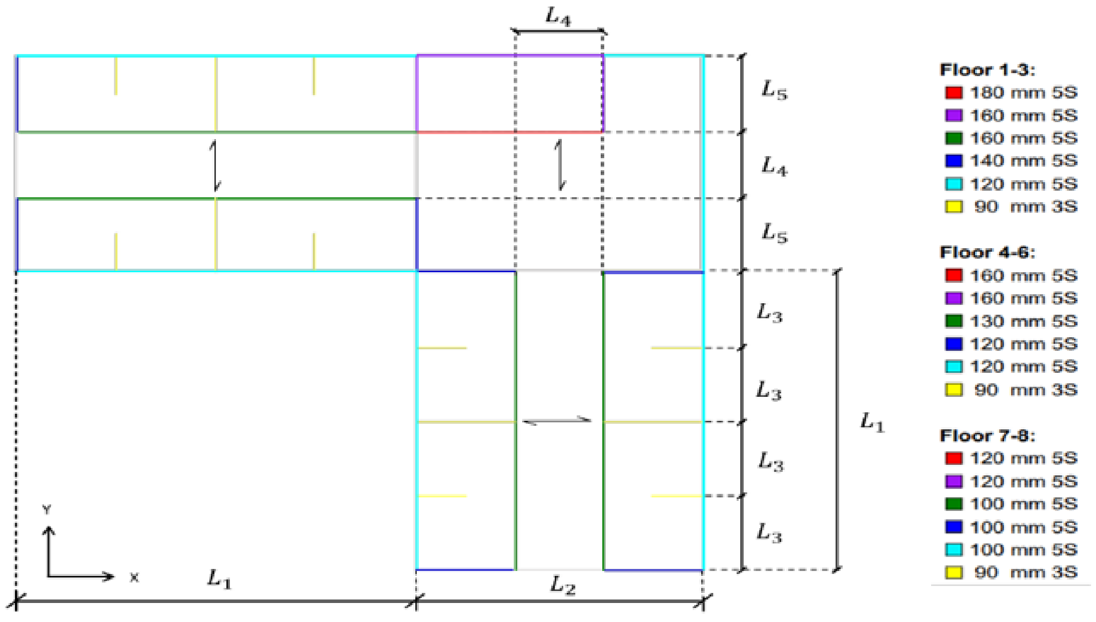
Mode	**Natural Frequencies [Hz]**			**% Var**	**Initial MAC**	**Updated MAC**
	Initial FE ($f_{a,i}$)	Updated FE ($f_{a,u}$)	Experimental ($f_{e,i}$)	$\frac{f_{a,u} - f_e}{f_e}$		
1	1.988	1.917	1.913	0.209	1.000	1.000
2	3.139	2.455	2.414	1.698	0.999	0.998
3	2.744	2.697	2.693	0.149	1.000	1.000

Effect of Variations in Building Footprint

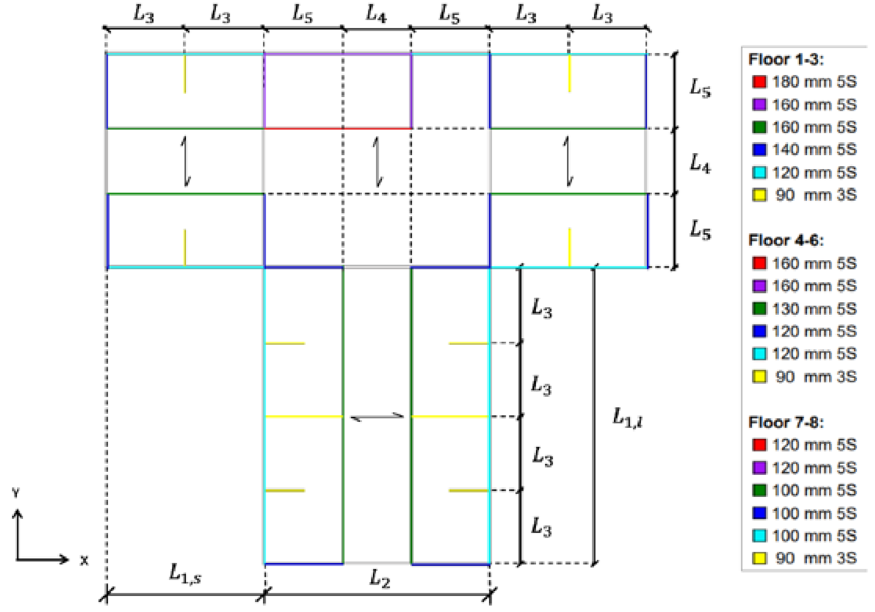
- Application of the FE calibrated model in assessing:
  - ❖ effects variations in the plan geometry and mass of CLT buildings has on the ordering and nature of lower order natural frequencies and mode shapes
  - ❖ modal participation



(b) Floor plan variation Geo-2



(a) Floor plan variation Geo-1



(c) Floor plan variation Geo-3

Effect of Variations in Building Footprint

Table 9. Effects of variations of plan geometry on natural frequencies and mode types. (Table view)

Mode order	Natural frequencies (Hz)				Mode shape		
	*Geo-0	Geo-1	Geo-2	Geo-3	**UX	UY	RZ
1	1.92	2.40	2.26	2.35		✓	
2	2.45	2.45	2.54	2.40	✓		
3	2.70	3.04	2.93	3.09			✓
4	6.25	7.02	6.81	6.94		✓	
5	6.94	7.27	7.31	7.07	✓		
Eccentricity (m)	$e_x = e_y = 0$	$e_x = e_y = 4.4$	$e_x = e_y = 4.2$	$e_x = e_y = 2.9$			

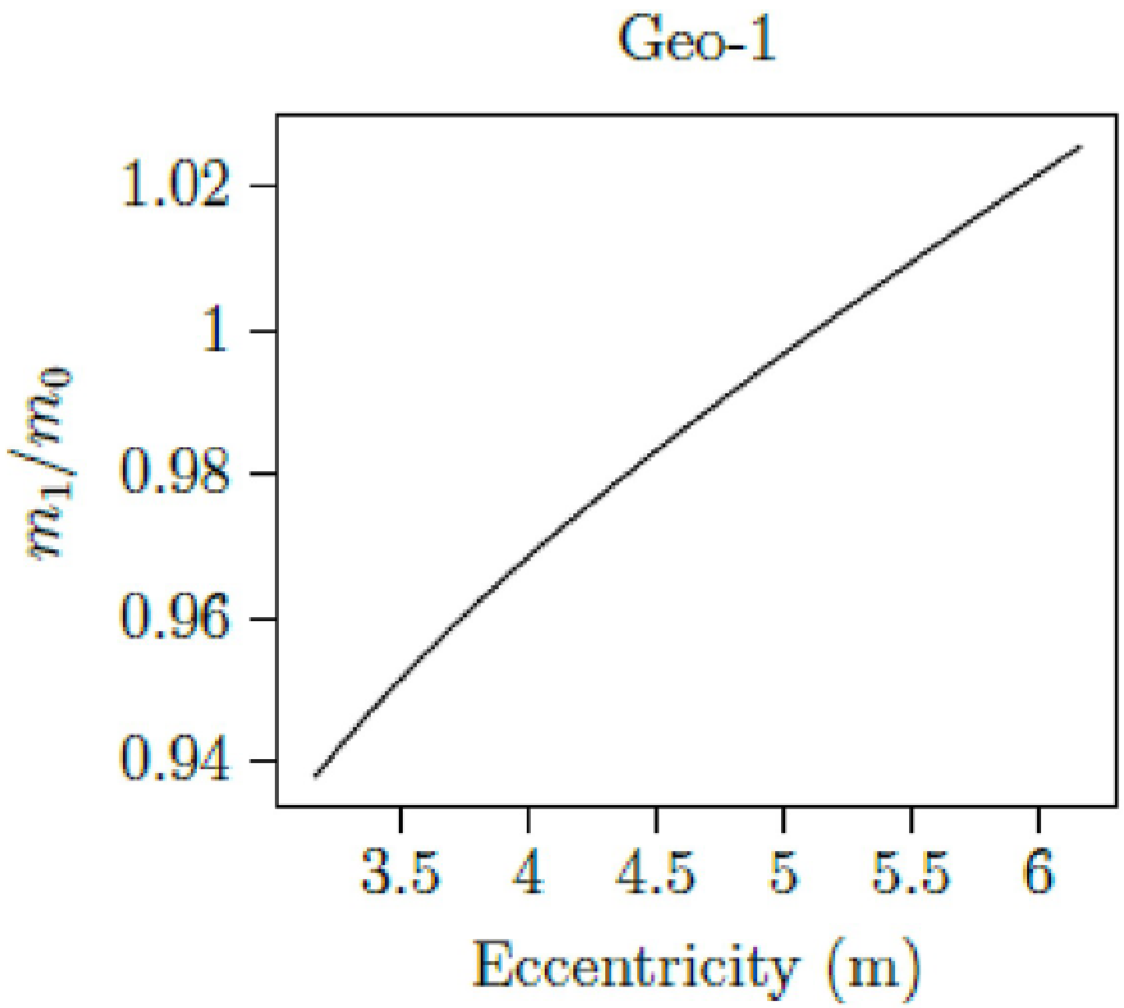
*Geo-0 is the reference (updated FE model) building model, Geo-1, -2 and -3 represents building models with footprint variations.

Table 10. Number of modes contributing to 90% mass participation. (Table view)

	Geo-0		Geo-1		Geo-2		Geo-3	
	x-dir	*y*-dir	*x*-dir	*y*-dir	*x*-dir	*y*-dir	*x*-dir	*y*-dir
Number of modes	53	55	39	38	39	38	36	33

Effect of Varying the eccentricity on Footprint Geo-1

- The eccentricity defined as the distance between the centre of gravity of masses and stiffnesses
- Is varied by additional masses due to increases in wall volumes since the chosen plan area (Geo-1) in m^2 is kept constant
- Enabled by Python scripts iterations
- The mass variations are normalized to the Geo-1 mass, m_0
- The first three natural frequencies are observed

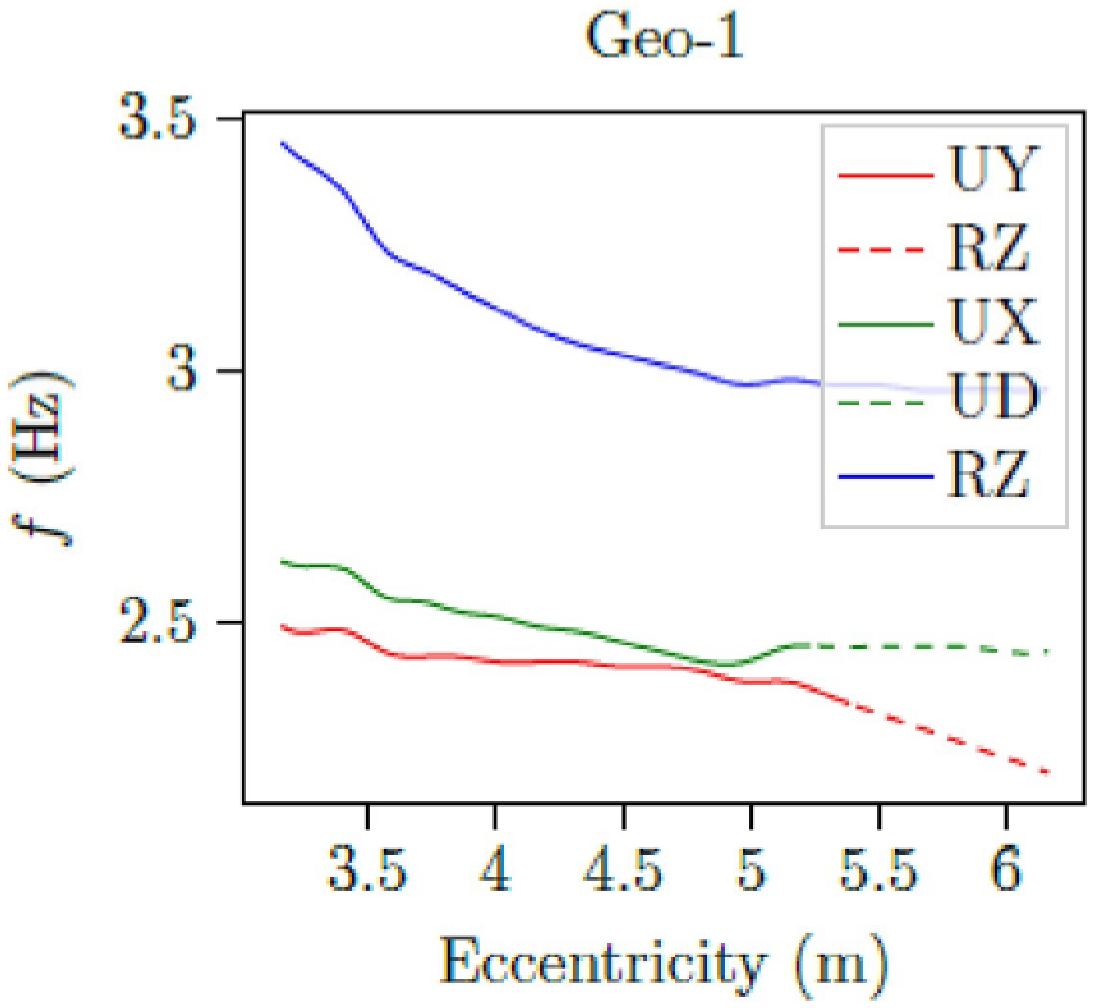


Effect of Varying the eccentricity on Footprint Geo-1

❑ Observations:

- An increase in eccentricity results in increased redistribution of masses without corresponding increases in modal stiffnesses, thereby reflecting decreases in the first three natural frequencies.

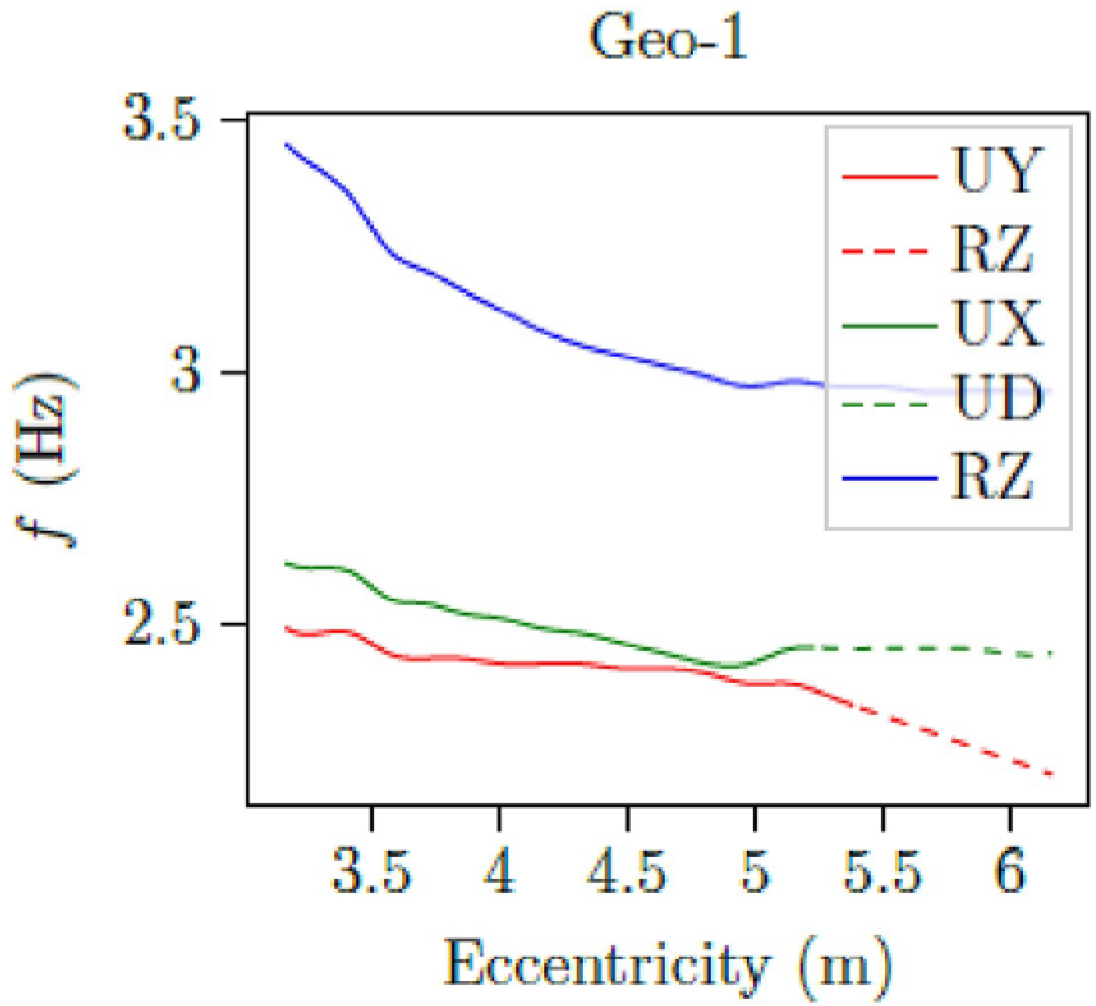
- A dotted line follows the variations in the mode shapes. UX is a translational mode shape in the *x*-direction, UY is a translational mode shape in the *y*-direction, UD is a translational mode shape in the diagonal (UX + UY) direction, and RZ torsional mode shape about z-axis



Effect of Varying the eccentricity on Footprint Geo-1

❑ Observations:

- A practical design implication is that both architectural and structural engineering design choices of CLT buildings should ensure construction features, including building footprint, shear walls and other lateral force resisting systems (LFRS) that limit eccentricities



Conclusions

- Using Finite Element model simulation techniques is a viable cost-effective alternative to expensive field measurements for determining vibration characteristics of mid-rise CLT buildings
- The approach predicts with reasonable accuracy effects of architectural and engineering design decisions on the dynamic responses of CLT buildings that have not been constructed to everyday ambient dynamic forces or forces generated by extreme events
- FE techniques show that flexible connections between wall and horizontal CLT elements should be accounted for in engineering design calculations. This is because the presence of metal shear connectors and tie-down anchors in connections alters natural frequencies and mode shapes
- Choices of design variables for CLT buildings must be done in a manner that limit eccentricities


Thank you