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INFLUENCE OF FLOOR EFFECTS ON THE SEISMIC PERFORMANCE OF CROSS-LAMINATED TIMBER STRUCTURES

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ABSTRACT: Despite the in-plane and out-plane performance of nail-laminated timber-concrete composite (NLTCC) floors having been widely investigated, detailed influence mechanisms of floors on seismic performance of structures is still lacking. In this paper, the influence of NLTCC floors on the seismic behaviour of cross-laminated timber (CLT) structures was investigated. Nonlinear finite element models for CLT structures were developed. A series of parametric analyses was conducted, considering stiffness of wall-to-floor connections and in-plane stiffness of NLTCC floors. The seismic performance, such as inter-story drift ratios (ISDR), roof drift ratios (RDR) and in-plane shear drift (ISD), were obtained from nonlinear dynamic time history analyses. The influence of stiffness of wall-to-floor connections and in-plane stiffness of NLTCC floors on structural seismic performance was quantified. The results showed that ISDR and RDR exhibited similar trends. Increasing floor stiffness reduced the maximum RDR by 8.75% and 19.59% for structures with identical wall-to-floor connection stiffness. The maximum ISD in CLT structures was negatively correlated with floor stiffness and wall-to-floor connection stiffness.

KEYWORDS: Wall-to-floor connection, nail-laminated timber-concrete composite floor, cross-laminated timber shear wall, seismic performance

1 – INTRODUCTION

Nail-laminated timber (NLT) is a mass timber product that is more cost-effective than cross-laminated timber (CLT) and is typically used for floors and roofs[1]. The Nail-laminated timber concrete composite (NLTCC) floors, formed by nailing the oriented strand board (OSB) panels to the NLT and pouring a layer of concrete, exhibits superior fire resistance and vibration performance, comparing to timber floors or concrete slabs[2].

Most studies focus on the in-plane and out-plane performance of NLT or NLTCC floors. Gan et al.[3] investigated the push-out performance of inclined screw shear connectors in NLTCC floors. Results indicated that the slip modulus and shear capacity were in positive and linear correlation with screw nominal diameter and penetration length. Li et al.[4] developed an analytical approach to evaluate the interal force in NLT, taking into account the distinct properties of its laminations. Based on the analytical and experimental results, the finite element (FE) models were established, which could effectively predict the bending performance of NLT. Feng et al.[5] tested the bending performance of two kinds of dimension lumber utilized as the laminations for the NLT specimens. The results showed that the mean bending strength of laminations primarily influenced the bending strength of NLT. Adema et al.[6] investigated the bending performance of NLTCC floors and evaluated failure modes, load–mid-span deflection relation, bending stiffness, and timber-concrete slip. The use of a multi-span configuration for floors offered a simple and effective way to reduce deflections.

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Despite the in-plane and out-plane performance of NLTCC floors having been widely investigated, limited studies were found in the seismic performance of structures considering NLTCC floors. The performance of wall-to-floor connections and the in-plane performance of floors, however, was proved to play a critical role in seismic performance of other structural systems [7][8][9]. Zhang et al. [10] investigated the influence of the hold-downs, vertical (wall-to-wall) and horizontal (wall-to-floor) shear connections between the CLT panels on the period and stiffness of buildings. The results show that the horizontal shear connections were the most essential parameter and the influence of connection stiffness decreased with the increase of building height. Yang et al. [11] conducted a shake table test on a two-story concrete building. The building employed flexible wall-to-floor connections along the long span direction and isolating wall-to-floor devices in the short span direction. The results indicated that flexible connection could fully transfer the acceleration while isolated connection could transfer the acceleration by the steel tongue in beam impacting and sliding.

Based on the previous literature, the influence investigation on the NLTCC floors in CLT structures seems to be relatively lacking.This paper focuses on the influence of NLTCC floors on the seismic behaviour of CLT structures. Nonlinear FE models were developed for such structures. The model was then utilized in nonlinear dynamic time history analyses to explore the influence of stiffness of wall-to-floor connections and in-plane stiffness of NLTCC floors. The structural performance was compared in terms of inter-story drift ratios, roof drift ratios and in-plane shear drift.

2 – NUMERICAL MODELLING

2.1 BASIC INFORMATION

The CLT structures were designed in a region of high seismicity in China. The site category is the second group of Class III and the intensity of seismic precautionary was assumed to be VIII[12]. The width and length of the structure were 13.2m and 18.0m, and the height of each story was 3.3m.The plan layout was shown in Figure 1. The mass consists of frame weight, CLT shear walls, NLTCC floors self-weight and additional mass.

The NLTCC floors were constructed using 38 mm × 140 mm spruce-pine-fir (SPF) lumber, 11.5 mm thick oriented strand board (OSB) panels, and a 60 mm thick concrete topping slab. For the CLT shear walls, 175mm-thick panels manufactured from graded No.2 and better [13] SPF lumber were selected. 6mm × 80mm self-tapping screws (STSs) were used as fasteners for connecting floors and walls. The beams and columns were constructed using SPF glulam. The column section for the 3rd and 4th floors was 400mm×400mm,whicl for the 1st and 2nd floors,it was 300mm×300mm. The beam section was 500mm×280mm in frame subsystem. The design paramaters of connections including wall-to-floor connection and beam-to-column connection, were given in Table 1. The configurations of wall-to-floor connections were shown in Figure 2.

Table 1: Design parameters of connections

Connection	Steel plate thickness (mm)	Fasteners at columns or wall ends	Fasteners at beam or floor ends
Beam-to-column	16	9×M24	6×M24
Hold-down	5	12×Φ6×80	12×Φ6×80
Angle-bracket	5	6×Φ6×80	M22

2.2 NUMERICAL MODEL

Nonlinear FE models were developed using the Open System for Earthquake Engineering Simulation (OpenSees) framework. The glulam columns and beams are modeled as elastic beam-column elements, as earthquake damage in glulam frames mainly occurs at the connections[14]. The Young's modulus of the elastic beam column elements is 9500Mpa. The edge CLT shear walls near the floors were modelled using fiber sections. The middle CLT shear walls were modelled using elastic Timoshenko beam column elements[15]. The NLTCC floors were modelled using two-node-link elements.

The connections between shear walls and floors were simulated by zero-length elements and DowelType model. The mechanical properties of NLTCC floors and wall-to-floor connections were obtained from test results and other authors[16]. The nonlinear behavior of beam-to-column and column-to-base connections were calibrated based on the load-displacement relationship of screwed joint groups, obtained from experimental data provided by He et al[17] .Figure 3 illustrates the the arrangement of wall-to-floor connections in CLT shear wall, including the hold-down and angle-bracket connections. The load-displacement relationship of different floor stiffness was shown in Figure 4.

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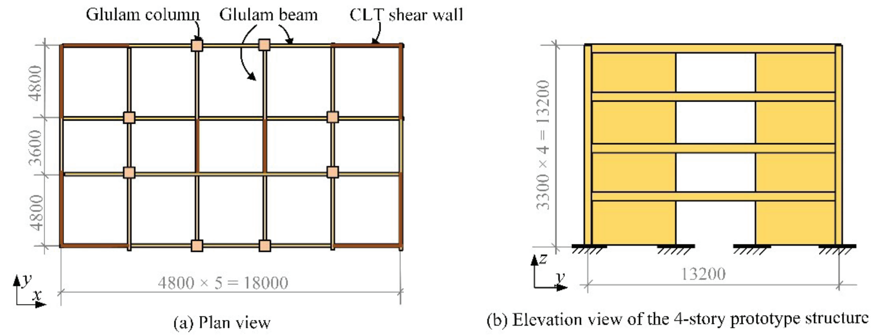


Figure 1. Layout of prototype structures (unit: mm)

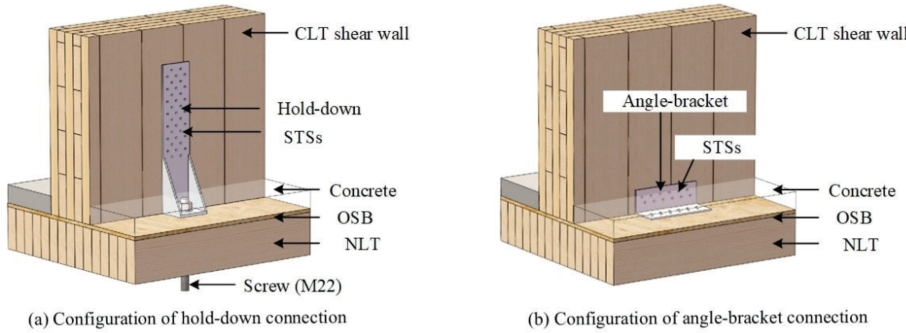


Figure 2. Configuration of wall-to-floor connections

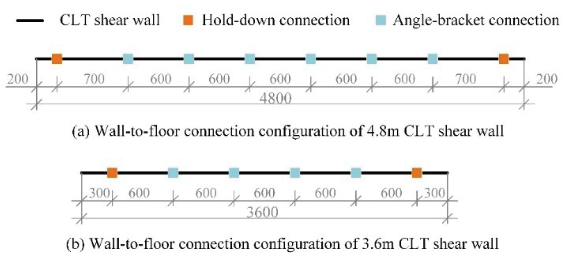


Figure 3. Configurations of wall-to-floor connections in CLT shear walls

2.3 SEISMIC INPUT

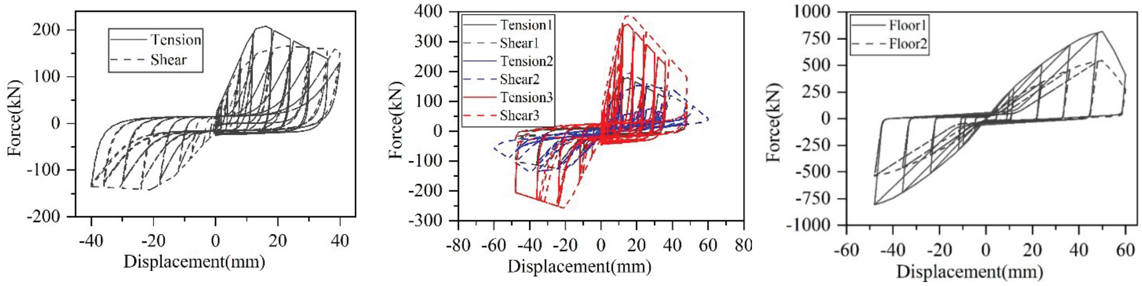
Ground motion records are essential for seismic time-history analysis. Selecting appropriate records ensures more accurate structural response predictions. In this study, the seismic intensity and site conditions matched those in reference [15], so the same 30 ground motion records from the PEER NGA-West2 database were used. These records were scaled to match the design spectrum for rare earthquakes, covering a period range of 0.14s to 2.0s to include the fundamental periods of the structures.

The fundational period was 0.48s with the first-mode shape in y-direction of the four-story structure. Thus, the subsequent nonlinear dynamic time-history analysis focuses on seismic performance in y-direction, with seismic excitation applied along this direction.

3 – PARAMETRIC ANALYSIS

In order to investigate the influence of NLTCC floors on the seismic performance of CLT structures, a series of parametric analyses was conducted. Nonlinear FE models were used for parametric analyses. Two variables, i.e., the stiffness of wall-to-floor connections and the in-plane stiffness of NLTCC floors, were considered in the parametric analysis.

The stiffness of the floors amd connections is characterized by their shear stiffness. The details were given in Table 2. The floor stiffness of F1,F2 and F3 refers to 14.74kN/mm, 22.10kN/mm and rigid floor. The hold-down connection stiffness of HD1 refers to 6.73kN/mm. The Angle-bracket connection stiffness of AB1, AB2 and AB3 referes to 6.53kN/mm, 9.55kN/mm and 13.06kN/mm.



(a)Hold-down connection (b) Angle-bracket connections (c) NLTCC floors

Figure 4. Load-displacement curves of connections

Table 2: Stiffness details for floors and connections

Model	Floor Stiffness (kN/mm)	Wall -to-floor Connection Stiffness (kN/mm)	
		Hold-down	*Angle-brackeet*
M1	F1	HD1	AB1
M2	F1	HD1	AB2
M3	F1	HD1	AB3
M4	F2	HD1	AB1
M5	F2	HD1	AB2
M6	F2	HD1	AB3
M7	F3	HD1	AB1
M8	F3	HD1	AB2
M9	F3	HD1	AB3

3.1 MAXIMUM INTER-STORY DRIFT RATI OS

The inter-story drift ratios (ISDR) represents a significant parameter for evaluating structural seismic performance, which quantifies both the deformation and damage extent of structures. The maximum ISDR of the structures were illustrated in Figure 5 and Figure 6.

The results of maximum ISDR showed that the maximum and minimum of CLT structures were 0.72% and 0.21% ,respectively. The maximum usually happened on the top story and the minimum usually happened on the lower story, which can be explained by lower stiffness redundancy of the top story. The higher floor stiffness leaded to the lower maximum ISDR, with the same wall-to-floor connection stifness. The higher stiffness of wall-to-floor connection could effectively reduce the inter-story deformation.

3.2 MAXIMUM ROOF DRIFT RATIOS

The maximum RDR for prototype structures were illustrated in Figure 7. The results showed that the maximum and minimum RDR of prototype syructures were 0.62% and 0.32%, respectively. The impact of wall-to-floor connection stiffness and floor stiffness on RDR was similar to that on ISDR. For example, increased floor stiffness resulted in reduced maximum RDR with the same wall-to-floor connection stiffness. The maximum RDR of structures were decreased by 8.75% and 19.59%(e.g., M2, M5 and M8). The AB2 connection had lower shear capacity compared to other connections, resulting in larger RDR for structures with the same floor stiffness. This is because the connection was prone to failure under the earthquake.

3.3 MAXIMUM IN-PLANE SHEAR DRIFT

The maximum ISD serves as a crucial parameter for assessing the in-plane shear deformation of the prototype structures. The maximum ISD of the prototype structures is plotted in Figure 8 and Figure 9. Due to the stronger stiffness of the structures, the in-plane shear drift of the floors was relatively small, all values less than 0.015mm.

The maximum and minimum of ISD were 0.009mm and 0.004mm, respectively. The larger maximum ISD usually occurred in the 4^{th} story, which could be explained by the weaker stiffness of the top story in structures. Prototype structures with greater floor stiffness exhibited reduced ISD compared to those with lower floor stiffness. This phenomenon could be attributed to the enhanced ability of floors to distribute shear forces more effectively, thereby reducing horizontal deformation. For the prototype structures witih rigid floor stiffness(e.g., M7, M8, M9), the maximum ISD were similar due to the effective overall coordination of floors.

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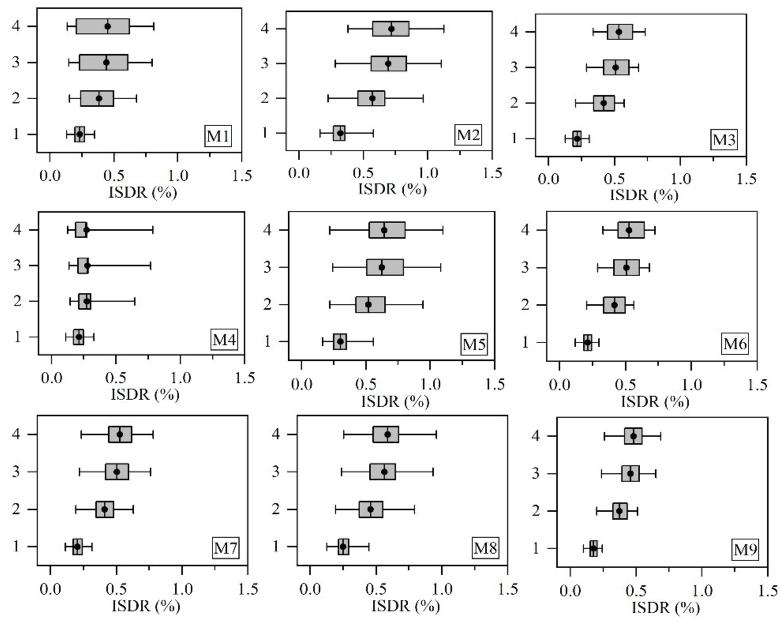

Figure 5. The maximum ISDR of CLT structures.

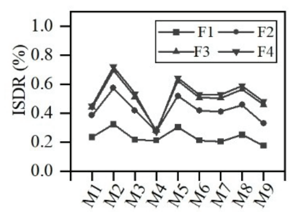

Figure 6. The average of maximum ISDR of CLT structures.

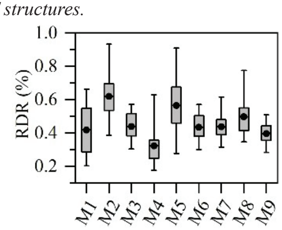

Figure 7. The maximum RDR of CLT structures.

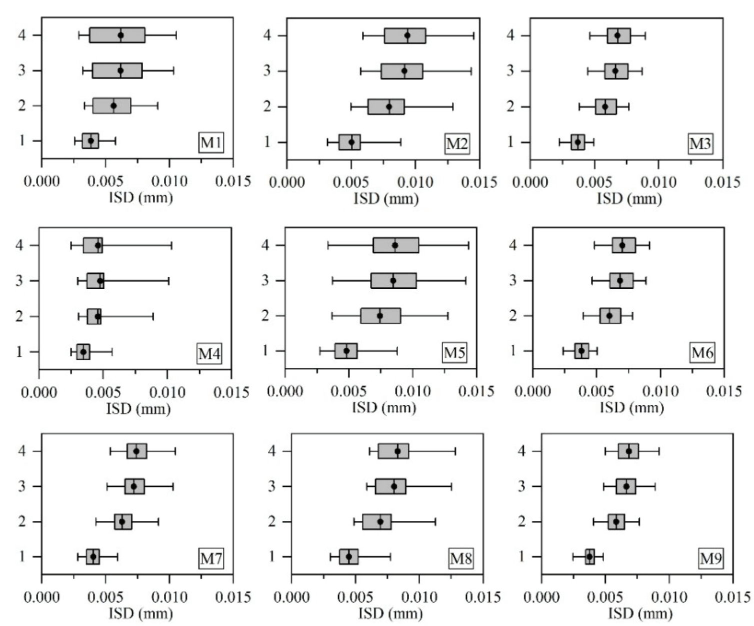

Figure 8. The maximum ISD of CLT structures.

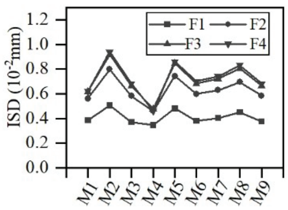

Figure 9. The average of maximum ISD of CLT structures

4 –CONCLUSIONS

This paper presents modelling strategies and parametric studies on the influence of NLTCC floors on the seismic behaviour of CLT structures. A series of parametric analyses was conducted, considering stiffness of wall-to-floor connections and in-plane stiffness of NLTCC floors. The conclusions are summarized as follows:

(1) The maximum ISDR results indicated that the CLT structures had a maximum value of 0.72% and a minimum value of 0.21%. With the same wall-to-floor connection stiffness, increased floor stiffness resulted in smaller maximum ISDR.

(2) The maximum RDR and ISDR exhibited similar trends. The maximum RDR of structures with the same wall-to-floor connection stiffness, were decreased by 8.75% and 19.59%, as the floor stiffness increased.

(3) The maximum ISD was typically observed in the top story, due to the "whiplash effect". The analysis revealed that floor stiffness and wall-to-floor connection stiffness were negatively correlated with ISD.

5 – REFERENCES

[1] Natterer J K. "New technologies for engineered timber structures." In: Progress in Structural Engineering and Materials 4(3) (2002), pp: 245-263.

[2] Hong, K. E. M. "Structural performance of nail-laminated timber-concrete composite floors". Master thesis. Applied Science, Faculty of; Civil Engineering, Department of University of British Columbia, 2017.

[3] Gan Z, Sun Y, Sun X, et al. "Push-out performance of inclined screw shear connectors used in nail-laminated timber-concrete composite." In: Construction and Building Materials, 366 (2023), pp. 130175.

[4] Li Z, Feng W, He M, et al. "Bending performance of nail laminated timber: Experimental, analytical and numerical analyses." In: Construction and Building Materials, 389 (2023), pp. 131766.

[5] Feng W, He M, Ou J, et al. "Bending performance of nail laminated timber (NLT): Experiments and probabilistic modelling based on Monte Carlo simulation." In: Engineering Structures, 323 (2025), pp. 119317.

[6] Adema A, Chacón M F, Santa María H, et al. "Flexural performance of full-scale two-span nail-laminated timber concrete composite slabs." In: Construction and Building Materials, 432 (2024), pp. 136528.

[7] Tomić I, Vanin F, Božulić I, et al. "Numerical simulation of unreinforced masonry buildings with timber diaphragms". In: Buildings 11 (2021), pp.205.

[8] Solarino F, Oliveira D V, Giresini L. "Wall-to-horizontal diaphragm connections in historical buildings: A state-of-the-art review." In: Engineering structures, 199 (2019), pp.109559.

[9] Loss C, Rossi S, Tannert T. "In-plane stiffness of hybrid steel–cross-laminated timber floor diaphragms". In: Journal of Structural Engineering 144 (2018), pp. 04018128.

[10] Zhang X, Pan Y, Tannert T. "The influence of connection stiffness on the dynamic properties and seismic performance of tall cross-laminated timber buildings" In: Engineering Structures 238 (2021), pp. 112261.

[11] Yang Q, Henry R, Lu Y. "Wall-to-floor connection behavior in a low-damage concrete wall building." In: Proceedings of the 2021 New Zealand Society for Earthquake Engineering Annual Technical Conference(2021), pp. 94.

[12] Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). GB 50011-2016 - Code for seismic design of buildings. Beijing, China; 2016.

[13] National Lumber Grading Authority (NLGA). Standard grading rules for Canadian lumber. Vancouver, Canada; 2014.

[14] Li Z, Luo J, He M, et al. "Seismic performance of multi-story glulam post-and-beam structures reinforced with knee-braces." In: Journal of Building Engineering, 44 (2021), pp. 102887.

[15] Wang X, He M, Li Z. "Evaluation of engineering demand parameters for seismic analyses of CLT-glulam hybrid structures." In: Engineering Structures, 296 (2023), pp. 116958.

[16] Gan Z, Sun Y, Li Z, et al. "Experimental and numerical investigation on the in-plane performance of nail-laminated timber floor." In: Journal of Building Engineering, 96 (2024), pp.110509.

[17] He M, Luo J, Tao D, et al. "Rotational behavior of bolted glulam beam-to-column connections with knee brace." In: Engineering Structures, 207 (2020), pp. 110251.

https://doi.org/10.52202/080513-0481