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EQUIVALENT SHELL MODEL FOR CLT SHEAR WALLS

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ABSTRACT: This paper presents a numerical modeling approach of low computational cost for the representation of CLT shear walls, using an orthotropic virtual material assigned to a shell element. The proposed model is based on stiffness equivalency, calibrated through analytical expressions that consider both shear deformation and overturning effects, aiming to replicate the displacement behavior of CLT walls under lateral loads. To evaluate its performance, a simplified four-story building was modeled using finite element analysis software and analyzed under seismic loading conditions defined by the Chilean code NCh433. The behavior of the proposed equivalent shell model was compared against three alternative modeling strategies: a nonlinear model with springs representing connectors, a linear model with shear springs, and a rigid model assuming fully fixed joints. The comparison focused on global lateral displacements and deformation patterns. Results show that the equivalent shell model achieves displacement values similar to those of the nonlinear reference model, while significantly reducing modeling complexity. The findings suggest that this method offers a viable alternative for structural analysis of CLT systems, particularly in preliminary design stages or in contexts where simplified modeling is required without disregarding key behavioral characteristics of CLT shear walls.

KEYWORDS: timber, etc (max 5 keywords)

1 – INTRODUCTION

The structural modeling of prefabricated timber systems presents specific challenges associated with their inherent construction logic and mechanical behavior. One of the primary sources of complexity in the numerical modeling of these systems lies in the role of the mechanical connectors, which govern the interaction between the prefabricated elements. These connectors often exhibit nonlinear behavior due to their unidirectional working condition, typically responding only under tensile forces. This partial activation, in conjunction with the geometric and material characteristics of the system, results in a complex stiffness profile that is not easily captured through conventional linear modeling strategies.

Cross-laminated timber (CLT) walls exemplify this modeling challenge. As monolithic wall elements composed of multiple layers of timber boards bonded orthogonally, CLT panels rely on mechanical connectors—such as angle brackets and hold-downs—to provide structural continuity and lateral resistance. The global behavior of CLT shear walls is thus significantly influenced by the localized behavior of these connections. In seismic or lateral loading scenarios, this results in a multi-component deformation response, where both panel shear and connector deformation—including sliding and uplift—must be accounted for to accurately estimate displacements.

To represent this behavior with fidelity, advanced modeling techniques are typically required. These include detailed finite element models where connectors are individually represented through spring elements with nonlinear stiffness curves calibrated from experimental data. While such nonlinear models provide high accuracy, their complexity and computational cost often limit their application to academic or research settings. On the other end of the spectrum, simplified models are frequently used in professional practice. These may treat the CLT wall as a rigid or linearly elastic element without appropriately accounting for connector flexibility. As a result, these models tend to underestimate displacements and fail to capture key behavioral modes such as uplift and sliding, leading to non-conservative assessments of structural performance under lateral loading.

In light of these limitations, the development of intermediate modeling strategies that offer a balance between accuracy and simplicity becomes relevant, particularly in the context of performance-based seismic design or preliminary structural analysis. Previous work with light-frame timber walls has demonstrated the potential of simplified modeling approaches based on stiffness equivalency. In these approaches, the global behavior of the wall system is preserved by defining equivalent stiffness parameters that reflect the combined

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response of structural elements and connectors, without the need to represent each component individually.

Building upon this precedent, the objective of the present work is to explore the application of a similar methodology to CLT walls. Specifically, this research proposes the development of an equivalent shell model, in which the wall is represented as a continuous orthotropic material with mechanical properties calibrated to reproduce the axial and lateral stiffness of a conventional CLT shear wall. The calibration is based on analytical models that incorporate the deformation modes associated with shear panel distortion, connector sliding, and uplift due to hold-down elongation.

The proposed model seeks to offer a computationally efficient alternative for the structural modeling of CLT buildings, particularly in early design stages or in contexts where high-fidelity modeling is not feasible. By validating the model against more detailed nonlinear simulations, the study aims to assess the extent to which such simplifications preserve the essential characteristics of CLT wall behavior and to identify the limitations and potential applications of the equivalent shell modeling strategy.

2 METHODOLOGY

This research is based on the numerical development of a virtual material, whose physical properties are determined through stiffness compatibility, both in the axial and lateral directions. The model has been developed based on previous work in which the same approach was used, but to model light-frame walls [1]. To understand the validity and applicability of the proposed model, a simplified typology of a building with CLT shear walls was studied, which has been analyzed under the seismic demands proposed by the Chilean code NCh433 [2], and its performance has been studied, in addition to the proposed model, with a selection of significant methodologies defined through a state-of-the-art study.

2.1 Discussion on the State of the Art of Numerical Models for CLT walls

The modeling of CLT walls has distinct levels of application, ranging from complex models with nonlinear characteristics to simplifications in the modeling of the solution, which deviate from an appropiated characterization of CLT shear walls. In order to generate comparison points with the proposed model in this article, three different methodologies for modeling CLT walls will be studied. These methodologies will be used to calculate lateral stiffness; while axial stiffness is a relevant component in the development of the proposed model, the inclusion of this axis in the methodologies is simply analyzable in the models used, therefore, its analysis and comparison with the proposed model will not be deepened. Thus, the models to be studied are: A nonlinear numerical model, a linear numerical model with the integration of shear springs and a linear model in which all CLT joints are assumed to be rigid.

Before analysing the numerical models, an analytical methodology (AM), which describes the behaviour and components of deformation of a CLT wall is described. This methodology corresponds to a theoretical approach, in which the deformation of the wall is defined through the sum of its components associated with the shear deformation of the CLT panel, the sliding of the shear connectors and the uplift it will undergo at its corner as a result of the Hold Down traction. The model proposed by Casagrande [3] has been chosen as reference, where the component associated with the wall's bending is disregarded (Figure 1.a). Thus, the equation that defines its deformation, proposed in the simplification presented by Guindos [4], is as follows.

$$K_{Lat\ CLT} = \left(\left(\frac{V * h}{0.9 * b} - \frac{q * b}{2} \right) \frac{h}{V * 0.9 * b * K_{HD}} + \frac{h}{b * t_{clt} * G_{CLT}} + \frac{1}{n * K_d} + \right)^{-1} \quad (1)$$

Where: "V" is the shear force received by the wall, "h" is the height of the wall, "q" is the axial load received by the wall, "b" is the length of the wall. "K HD" is the stiffness of the hold down, "t clt" is the thickness of the CLT wall, "G CLT" is the apparent shear modulus of the CLT wall, "n" is the number of shear connectors, and "Kd" is the stiffness of the shear connectors.

Seting this as a base theorical approach, the methods for the numerical models that will be studied in the article are described below.

The model with nonlinear springs (NLM) is the most specific, as it incorporates the effective equivalent properties of the used CLT panel [5], which must be modeled with springs representing the connections and characterized by their nonlinear behavior. This corresponds to an analytical numerical model, where each element (panel or connector) is characterized through an area element, a spring, or supports; here, the springs have a nonlinear characteristic curve, to include their behavior related to their state of tension or compression (Figure 1.b). Although this model provides responses with a high degree of predictability, it is a model that requires great detail and capacity in modeling [5], [6], [7]

The Linear Model with Shear Spring (LMSS) is a methodological proposal that suggests a simplification of the NLM model [8]. Here, the effect of overturning is disregarded, and only the stiffening imparted by the shear shear connectors is considered. The level of analysis precision is reduced, but it results in significant savings in modeling, since applying a linear spring to one side of a shell element is a straightforward operation in most finite element software.

The Rigid Model (RM) utilizes only the equivalent properties of CLT to model an area element, which does not include springs on any of its faces and therefore assumes rigid connections within them. Given the relatively recent adoption of CLT construction systems, particularly in regions like Chile where such constructions did not exist until 2024 [7], the methodology of numerical modeling has primarily been confined to specialized research groups. Meanwhile, firms specializing in structural calculations have encountered challenges in adapting traditional modeling techniques, originally developed for reinforced concrete, to CLT structures. Recognizing these issues, this model emerges as a critical point of analysis, especially as it explicitly highlights the risks associated with using these methodologies in the seismic evaluation of CLT buildings.

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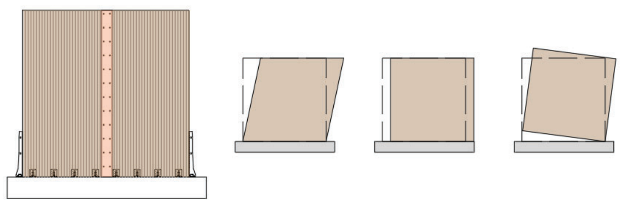
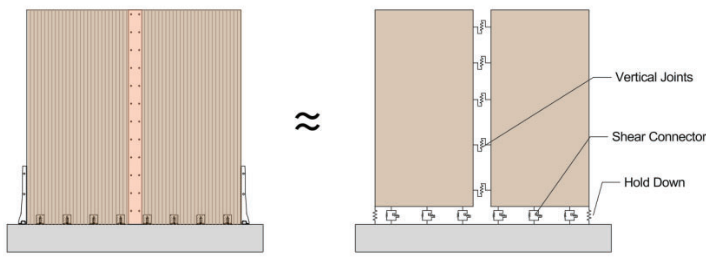
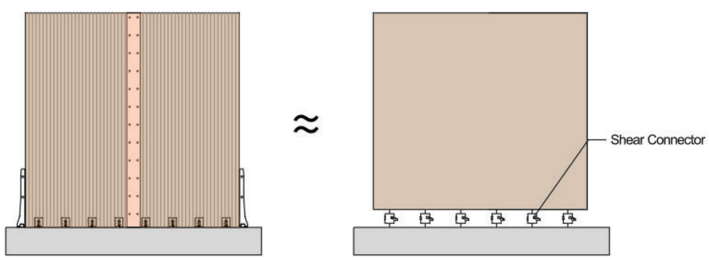
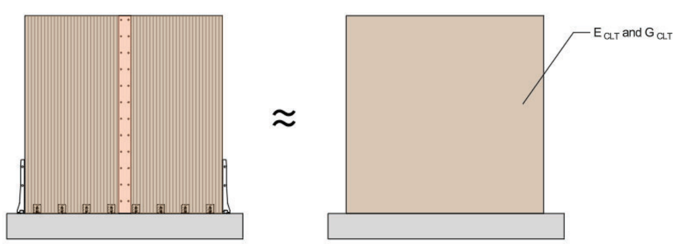
Methodology	Model	Observations
Analitic Model (AM)	 *Figure 1.a*	Theorycal equation taking in consideration: Shear effect of the panel, the sliding of shear connections and the up turning product of the Hold Down
Non Lineal Model (NLM)	 *Figure 2.b*	High precision model, includes non lineal stiffness curves for connectors but at increased numerical cost
Lineal Model with Shear Springs (LMSS)	 *Figure 3. c*	Simplification of the non lineal model, by the inclusion of only the shear connectors stiffness, neglecting the Hold Down
Rigid Model (RM)	 *Figure 4. d*	CLT model as reinforces concrete, no connection stiffness is considered, only the ortotropic equivalent properties of a CLT panel

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2.2 Equivalent Shell Model (ESM) for CLT shear walls:

In order to propose a methodology that uses the same simplifications of reinforced concrete, in the sense that no spring is used to model shearwalls, and to reduce numerical costs, an equivalent shell model is proposed to characterize CLT walls. It consists on the theoretical elaboration of a virtual material that characterizes, through the definition of its elasticity and shear moduli, the axial and lateral stiffness of a CLT wall. To characterize its axial stiffness, a compatibility is proposed between the net section of a wall, made up of the virtual material, and that of a CLT wall (Figure 2). To do this, and based on the stiffness of each layer, only the vertical lamellas in the wall are considered, which establishes the axial stiffness of a CLT wall. By equating this stiffness with the one of the element composed of the virtual material (Equation 3), the first unknown is clarified: E'.

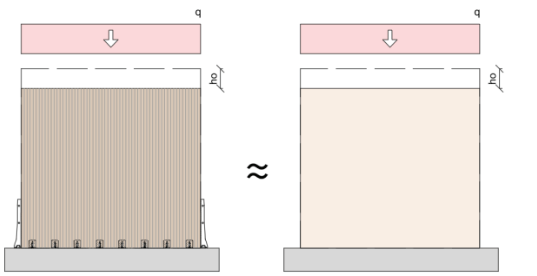

Figure 2, Axial discplacement compatibility of CLT Wall and Virtual Material Wall

$$\frac{E_{CLT} * A_{CLT}}{h} = \frac{E' * A'}{h}; A = A' = x * y \qquad (2)$$

$$E' = \frac{E_{CLT} * A_{CLT}}{A'} \qquad (3)$$

Next, to characterize the wall laterally, a deep beam model will be used to define the lateral stiffness of the equivalent material. Here, the lateral displacement is defined by its bending and shear component (Equation 4) [9]. On the other hand, the lateral stiffness of a CLT wall will be defined from the analytical model presented in Equation 5. These two equations are equated to establish the equivalence of stiffnesses; here, the wall composed of the virtual material has a different type of deformation as it does not include the lifting, but the total lateral displacement is the same in both models (Figure 3). Before making the equivalence, to use the analytical model as a reference, it is necessary to fully factorize the shear (V) received by the wall; for this purpose, the proposed traction reduction is disregarded, which allows defining the lateral stiffness of the wall with Equation 5. Once the stiffness equations for both systems are obtained, the equivalence is made, and Equation 6 is obtained, which defines the second required variable: G'.

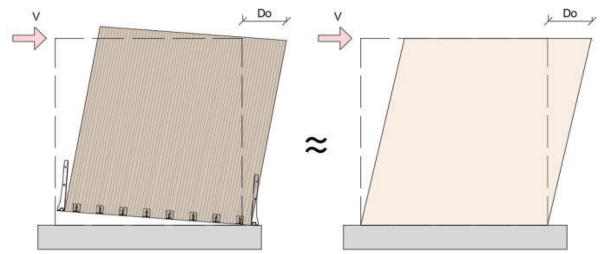

Figure 3, Lateral discplacement compatibility of CLT Wall and Virtual Material Wall

$$K'_{eq} = \left(\frac{3E'I'}{h^3} + \frac{G'A'}{1.2h}\right)^{-1} \qquad (4)$$

$$K_{Lat\ CLT} = \left(\frac{h^2}{0.81 * b^2 * K_{HD}} + \frac{h}{b * t_{clt} * G_{CLT}} + \frac{1}{n * K_d}\right)^{-1} \qquad (5)$$

$$G' = \frac{1.2h}{b} * \left(\frac{h}{b * t_{CLT} * G_{CLT}} + \frac{1}{n * K_d} + \frac{h^2}{0.81 * b^2 * K_{HD}} - \frac{4h^3}{E'b^3 t}\right)^{-1} \qquad (6)$$

By defining the E' and G' for the virtual material, a shearwall can be modeled, where the axial deflection (ho in Fig X) and the lateral deflection (Do in Fig X) are igualated. Thus, is possible to model an element with the same geometry as the CLT walls, but using a virtual material that considers the stiffness implied by the connectors, without the need to explicitly include them, significantly reducing the modeling and information processing time. Although the defined material is theoretically isotropic, it is necessary to define it as an orthotropic material, since the Poisson's ratio defined by the relationship between E' and G' is less than 0.2, so the material cannot be defined while maintaining this ratio

2.3 Simplified building

To evaluate the performance of the proposed model, a schematic typology of a building with CLT walls is considered. In this idealization of a building the distribution and detailing defined in Figure 4 to 6 has been considered. With the detailed information, it is possible to calculate the stiffness of the first-floor wall and the upper floors using Equation 5, resulting in K_{1F}=2041 kg/mm and K_{2-4F}=1315 kg/mm. On the other hand, to model the diaphragm, a semi-rigid diaphragm has been considered, defined according to Chen's proposal in the study of diaphragms for light-frame models [10] [11], which in turn are based on the performance of semi-rigid diaphragms defined in ASCE 41-06 [12].

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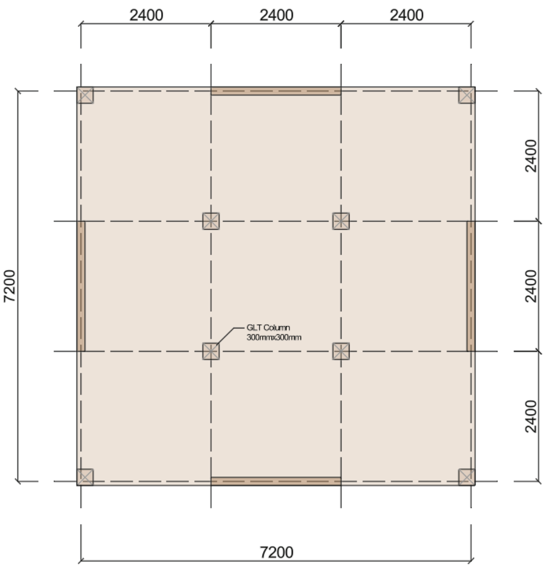

Figure 4, Floor plan of the simplified building

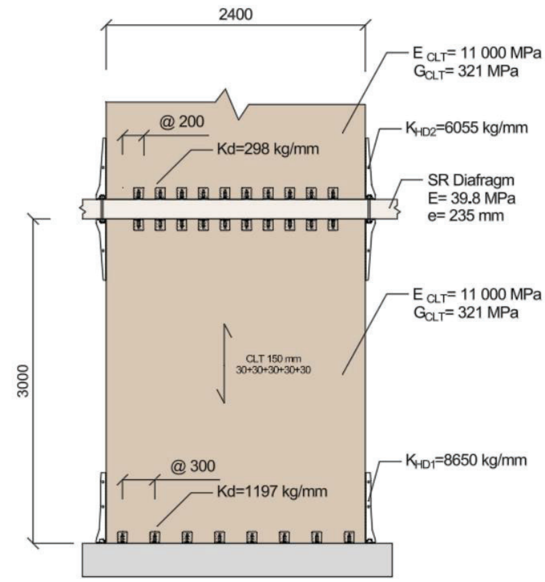

Figure 6, Properties of CLT and connectors

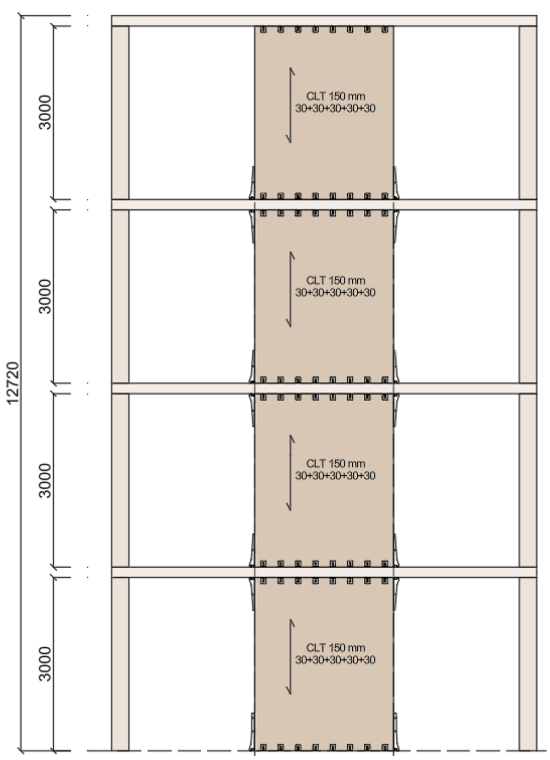

Figure 5, Perimetral elevation of the simplified building

For the calculation of the building's weights, a Self-Weight for the slab of 220 kg/m² and a Live Load of 200 kg/m² have been considered. With this weight, and assuming residential use, the Chilean seismic code NCh 433 [2] was used to calculate the distribution of seismic forces. A soil type B and a seismic zone 2 (Ao=0.3g) have been defined to determine the magnitudes of the forces. For calculating the modification factor R, which takes into account the ductility of the system, a value of R=2 was used, which defined a maximum seismic coefficient of 27%. The distribution of weights and seismic forces per floor is shown in Table 1.

Table 1: Seismic Properties of the Building

Story	Height	Seismic Weight	Seismic Force
	[m]	[ton]	[ton]
4	3	16,5	9
3	3	17,1	3.9
2	3	17,1	3
1	3	17,1	2,5

2.3 Numerical models used to study the building:

The described building has been modeled and analyzed on a FEA software according to the NLM, LMSS, RM methodologies, these results are compared with the behaviour of the Equivalent Shell Model (SEM). The distribution of stresses on a characteristic axis and the displacement achieved in each model have been calculated for all models and have been analyzed.

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3. RESULTS

The distribution displacements of the perimetral axis, by story, is presented in Table 2. Here, the absolute displacement for each of the studied models is presented.

Table 2: Seismic Performance of the studied models

Story	RM [mm]	SSM [mm]	NLM [mm]	ESM [mm]
4	51.7	58	187.5	187,5
3	35	40	144.6	144,6
2	19.3	22.5	64.8	91,7
1	6.8	7.8	22.2	34,9

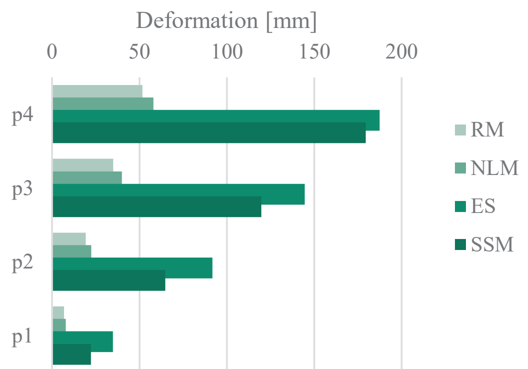

Figure 7, Displacement of the different models studied.

Additionally, in Figure 8, the deformation of a perimetral wall has been graphed on the same scale (1:10) for each model, where the difference in the type of displacement for each model can be clearly seen, as described in Figure 1.

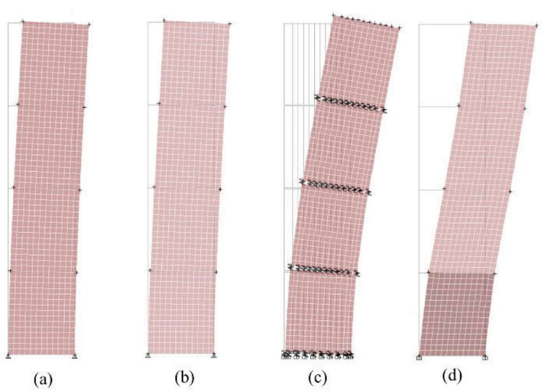

Figure 8, View of deformation of different models. (a) RM, (b) SSM, (c) NLM, (d) ES

The scale used (1:10), was defined so that the displacements of the models could be compared. Despite this, some relevant features in the models are not evident, such as the uplift in the NLM or the sliding between stories in the SSM.

6 – CONCLUSION

This study presented the development of a virtual material through stiffness equivalency for the modeling of CLT shear walls. By defining orthotropic elastic properties (E' and G') based on axial and lateral stiffness compatibility, the virtual material enables a simplified finite element representation of CLT walls without the explicit inclusion of nonlinear or semi-rigid connection elements.

A simplified multi-story building with CLT shear walls was analyzed under four different modeling strategies: a Nonlinear Model (NLM), a Linear Model with Shear Springs (SSM), a Rigid Model (RM), and the proposed Equivalent Shell (ES) model. These comparisons were focused on the resulting seismic displacements of the structure, calculated under the Chilean seismic code NCh433 for a zone 2 site condition.

The results show that the ES model replicates the displacement trends of the NLM with high similarity in terms of total displacements, where the roof displacement has a percentual difference of a 4%, while the average of porcentual difference of all stories corresponds to a 31%. These similarities are particularly relevant considering that the NLM includes a detailed representation of the nonlinear behavior of connectors and uplift, and is therefore regarded as the most accurate model in this study. This correlation supports the conclusion that the equivalent shell methodology effectively captures the global lateral behavior of a CLT shear wall system.

The RM and SSM models exhibited similar displacement trends between each other, which was expected due to the simplifications adopted in both methods. However, the SSM presented slightly larger displacements across all floors compared to the RM, as a consequence of incorporating the stiffness of shear connectors in the lateral behavior, while the RM assumes fully rigid joints. Despite their mutual similarity, both RM and SSM models deviate significantly from the NLM results. The base displacement of the NLM model, for instance, was approximately three times that of the RM model. This deviation suggests that using these models for design purposes could result in the overestimation of the lateral stiffness of the building and therefore lead to an underestimation of seismic demands. This has implications for both safety and serviceability evaluations and highlights the limitations of using overly simplified methodologies in CLT seismic design.

The Equivalent Shell Model (ESM), despite not including explicitly nonlinear connector behavior or uplift effects, offers a good approximation of the actual displacements, particularly in the upper stories. The modeling simplification it proposes—through the creation of a virtual orthotropic material—substantially reduces computational demand and user input requirements, and thus could be suitable for preliminary design or for integration into performance-based design frameworks that involve multiple iterations or sensitivity analyses.

Nonetheless, the accuracy of the ESM could be enhanced through the refinement of the analytical expressions used for lateral stiffness equivalency. The current expressions, based on simplified analytical models, do not capture all deformation modes, particularly those arising from uplift

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at wall corners and complex joint interactions. Improved analytical formulations or the inclusion of correction factors could bring the ESM's base displacement results closer to those of the NLM model, thereby increasing its applicability to detailed design phases.

The Equivalent Shell model constitutes an efficient and effective intermediate alternative between high-fidelity nonlinear modeling and overly simplified rigid modeling for CLT shear walls. It balances computational efficiency with predictive accuracy, especially when compared to conventional models that do not incorporate connection flexibility. Further improvements in the definition of lateral stiffness parameters could extend its use across a broader range of CLT structural typologies and seismic performance objectives.

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