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Advancing Timber for the Future Built Environment

ENHANCING THE SEISMIC PERFORMANCE OF HOLD-DOWN TIMBER TO CONCRETE CONNECTIONS VIA DUCTILE ANCHORS

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ABSTRACT: Anchor bolts embedded in concrete can play a critical role in the performance of Cross-Laminated Timber (CLT) walls under seismic loading. The hysteretic behavior of anchor bolts, characterized by stiffness degradation, pinching effects, and energy dissipation, influences the global response of CLT wall systems. This report explores the anchor bolt hysteresis in concrete and its impact on the dynamic performance of CLT walls, including stiffness, strength, deformation capacity, and energy dissipation. Numerical models are developed to highlight the interactions between anchor behavior and wall performance under cyclic loading.

KEYWORDS: Cross-Laminated Timber (CLT), Seismic Performance, Ductile Anchor

1 – INTRODUCTION

CLT walls are increasingly used in tall timber construction due to their superior seismic and environmental performance. The behavior of these walls during seismic events is significantly influenced by their connections like hold down and shear brackets. While these connections have been extensively studied, the effect of anchor bolts embedded in concrete foundations remains relatively unexplored. Anchor bolts may provide stability and transfer forces from the walls to the foundation, but their nonlinear response under cyclic loading—manifested as hysteresis—affects the overall seismic performance of CLT walls. This report examines anchor bolt hysteresis in concrete and its implications for the stiffness, strength, and energy dissipation of CLT wall systems.

2 – BACKGROUND

CLT is a sustainable, seismic-resistant material known for its prefabrication efficiency and carbon storage [1]. While CLT panels excel in resisting lateral loads, their seismic performance hinges on connections like hold-downs, shear brackets, and anchor bolts [2, 3].

Hold-downs and shear brackets are well-researched for their ductile hysteresis under cyclic loads [4]. In contrast, anchor bolts—critical for transferring forces to foundations—exhibit nonlinear behavior, including slip and concrete damage, leading to pinching hysteresis and stiffness loss [5, 6]. While these effects can reduce energy dissipation capacity [7], the inherent softness and hysteresis of anchor bolts may also introduce ductility to the system by redistributing forces and delaying brittle failure modes, a possibility underexplored in current research.

Current design standards (e.g., Eurocode 8, ASCE 7) oversimplify anchor bolts as linear-elastic components, neglecting their hysteresis [8]. This simplification risks inaccurate seismic performance predictions, particularly in high-risk zones where cumulative anchor damage may compromise system resilience [9]. Recent research underscores the need for advanced numerical models that capture anchor bolt nonlinearity to enable performance-based design [10]. Addressing this gap is critical to optimizing CLT wall systems for reliability under

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extreme seismic loads and leveraging potential ductility benefits from anchor bolt hysteresis

2.1 ANCHOR BOLT HYSTERESIS IN CONCRETE

The hysteresis loops of anchor bolts embedded in concrete are shaped by the combined nonlinear behaviors of the bolt, concrete and their interaction. In this report the experimental response of an M12 bolt both in shear and tension are utilized to incorporate the anchor hysteresis and its effect on the overall performance of the wall. Fig.1 represents the numerical anchor hysteresis both in shear and tension.

3 – NUMERICAL MODELING

A 2.5 × 2.5 m CLT panel was selected for modeling in OpenSees, where an isotropic material was used to represent its properties. For the connection modeling, the parallel material approach was employed to capture complex hysteretic behaviors by combining multiple material responses. This method is adopted for the representation of anchor bolts and their interaction with the hold down material under cyclic loads, capturing the nonlinear effects of hysteresis, stiffness degradation, and energy dissipation. Fig. 2 represents the parallel material modeling approach where two materials are combined so that strains are equal and stresses and stiffness's are additive. In such way for a CLT wall analysis, hold downs and anchor bolts are modeled as pinching04 material and combined as parallel material and assigned as a zero-length element at the base of the CLT wall.

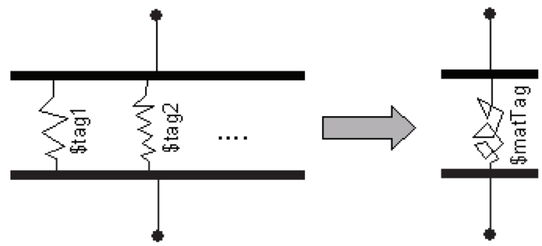

Figure 2. Parallel material in OpenSees [12]

hysteresis behavior of the hold-down in tension, modeled using the Pinching4 uniaxial material to capture its cyclic response, including pinching, stiffness degradation, and energy dissipation. This material was selected because it effectively replicates the nonlinear behavior observed in experimental tests. The calibration process involved adjusting key parameters to align with the experimentally obtained hysteresis loops. To represent the full anchorage behavior, the hold-down and anchor hysteresis from Fig. 1 were combined in a parallel material configuration, ensuring an accurate representation of force-displacement behavior. This approach was chosen to enhance the reliability of numerical simulations in predicting the seismic response of timber walls, providing a more realistic assessment of connection performance under cyclic loading.

3.1 DETAILED MODELING OF HOLD-DOWN CONNECTIONS IN CLT WALLS

For CLT walls, the hold-down connections play a dominant role in determining their overall capacity. While using a uniaxial material model provides valuable insights into the global behavior, a more detailed modeling approach is necessary to understand the effect of the anchor bolt within a parallel material framework.

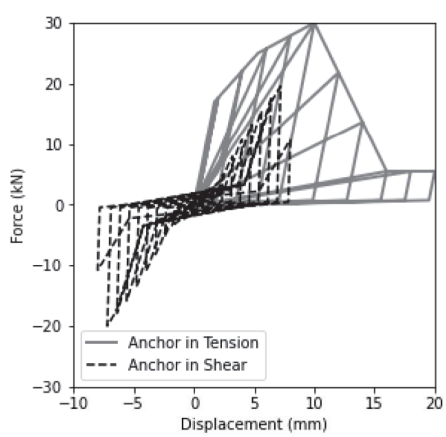

Figure 1. 1 M12 Anchor bolt hysteresis in concrete [11]

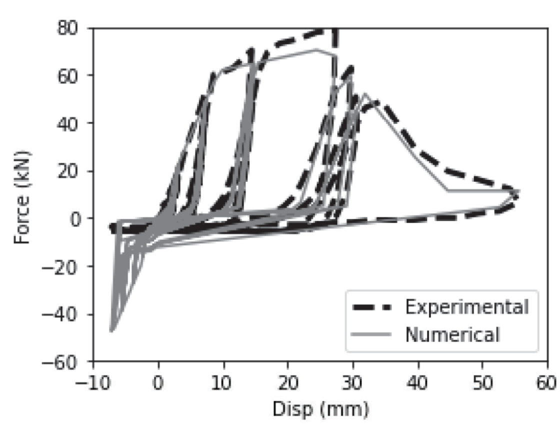

Figure 3. Hold down force vs displacement hysteresis [13]

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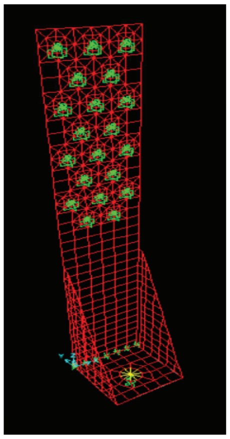

Figure 4. Hold down in SAP2000

To explicitly capture the influence of the anchor bolt, a hold-down connection model was developed in SAP2000, incorporating both nail and anchor effects. The key aspects of the numerical model, as shown in Figure 4, include:

- Nails modeled as nonlinear link elements to represent their inelastic behavior.
- Hold-downs represented using shell elements to simulate their structural response.
- Anchors implemented as both linear and nonlinear link elements to evaluate their effect on connection behavior.

Through this modeling approach, a vertical displacement was imposed to determine the tensile stiffness of the connection elements. The tensile resistance of the connection was quantified by summing the vertical forces of the nailed flange for an imposed displacement of 1 mm.

This detailed analysis provides a more accurate representation of the hold-down and anchor interaction, contributing to a better understanding of CLT wall behavior under seismic loading.

4 – RESULTS AND DISCUSSION

A cyclic analysis was conducted under the parallel material consideration to evaluate the effects of strength/capacity and energy dissipation in the system. The primary objective was to assess how the presence or absence of anchor hysteresis influences the overall structural response.

4.1 INITIAL STIFFNESS

Fig. 5 illustrates the impact of anchor hysteresis on the cyclic response of the system. The inclusion of anchor hysteresis does not lead to a significant change in the initial stiffness of the wall. This is primarily due to the relatively low capacity of the anchor bolt used in the analysis, which does not substantially contribute to the overall stiffness of the system. Since the initial stiffness is largely governed by the hold-down and the surrounding structural elements, the minor influence of the anchor bolt on this aspect becomes evident. The numerical results align with this observation, indicating that while the anchor bolt plays a role in the later stages of the response, its effect on the initial elastic behavior remains negligible.

4.2 DUCTILITY AND DEFORMATION CAPACITY

The presence of the anchor bolt enhances the ductility of the system, allowing it to undergo greater deformation before failure. This improvement in ductility is attributed to the inherent flexibility of the anchor bolt, which introduces additional yielding mechanisms that delay abrupt failure. As a result, the system can accommodate larger displacements without a sudden loss of strength. The increased ductility is further supported by the energy dissipation characteristics observed in the analysis, where the presence of the anchor allows for a more distributed and controlled load transfer. This behavior is crucial in seismic applications, where structures are required to sustain multiple cycles of loading without experiencing sudden failure.

4.3 ENERGY DISSIPATION

A comparative evaluation of energy dissipation between the two cases—one with anchor hysteresis and one without—demonstrates the beneficial role of the anchor bolt in improving the system's capacity to absorb and dissipate energy. The flexibility of the anchor bolt contributes to a more gradual redistribution of forces, which prevents premature failure and enhances overall performance under cyclic loading. The improved energy dissipation is particularly evident in the hysteresis loops, where the case with anchor hysteresis shows greater area enclosed within the cycles, indicating higher energy absorption. This characteristic is essential in seismic-resistant design, as it ensures that the structure can endure multiple loading cycles while minimizing damage accumulation.

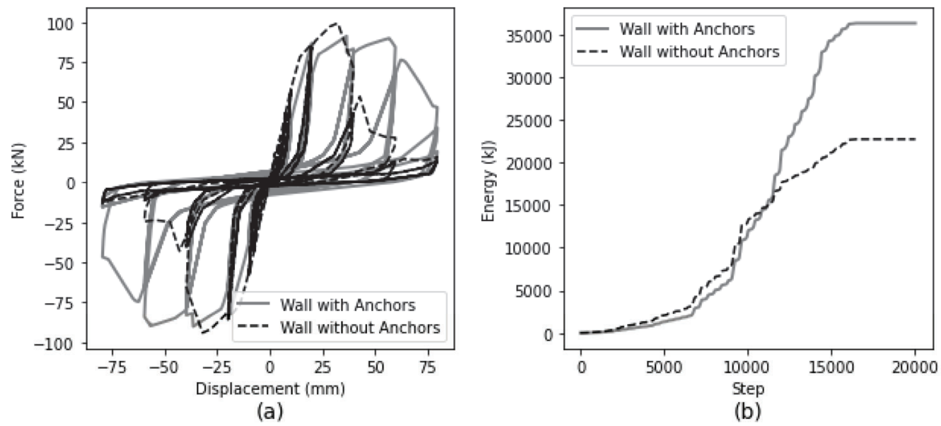

Figure 5. CLT wall response under anchor hysteresis

4.4 FAILURE MODE

In the absence of anchor hysteresis, the system exhibits a brittle failure mode, where the structural response remains linear until reaching maximum capacity, followed by an abrupt loss of strength. This brittle behavior is undesirable in seismic applications, as it limits the ability of the structure to sustain deformations beyond the elastic limit. However, when anchor hysteresis is considered, the failure mechanism transitions to a more controlled mode, allowing for progressive strength degradation rather than sudden collapse. This highlights the critical role of anchor hysteresis in enhancing the system's post-peak performance, ensuring that failure occurs in a ductile and predictable manner rather than through sudden fracture.

4.5 EFFECT OF HOLD-DOWN CAPACITY ON OVERALL PERFORMANCE

The hold-downs used in the analysis had limited strength, necessitating a numerical investigation of higher-capacity hold-downs to assess their impact on overall performance.

Comparison of Two Hold-Downs (Fig. 6) involves two types of hold-downs, HD1 and HD2. HD1 represents the hold-down with the capacity defined in Figure 3, while HD2 is a higher-capacity hold-down, achieved by increasing its backbone curve by 50%. Despite this increase in strength, HD2 retains the same pinching behavior and stiffness degradation characteristics as HD1. This comparison is essential for evaluating the impact of hold-down strength on wall performance, particularly in terms of load resistance and energy dissopation. dissipation.

4.6 INFLUENCE OF ANCHOR STIFFNESS ON HOLD-DOWN CONNECTION BEHAVIOR

The hold-down connection plays a critical role in the overall performance of the wall, with nails being the primary contributors to its load-bearing capacity. Therefore, understanding how the anchor stiffness affects the behavior of the nails is crucial for accurately assessing the system's response under cyclic loading.

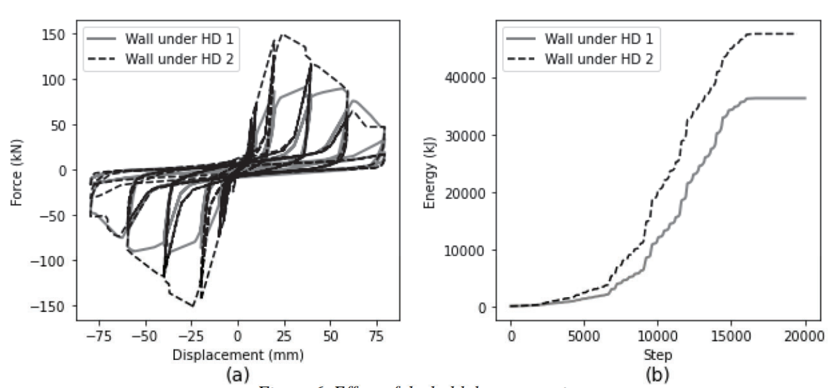

Figure 6. Effect of the hold down capacity

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To gain deeper insights into the behavior of the hold-down connection, a link element was introduced at the base to simulate the effect of anchor stiffness. This modification in the boundary condition allows for a more realistic representation of the connection behavior, ultimately influencing the global performance of the wall. Prior to include the anchor hysteresis the hold down model was analyzed against the experimental test by [13] and found that the numerical model predicts the response of the hold down reasonable. Fig. 7 provides the comparison of the deformed shape of the hold downs from the test and numerical model.

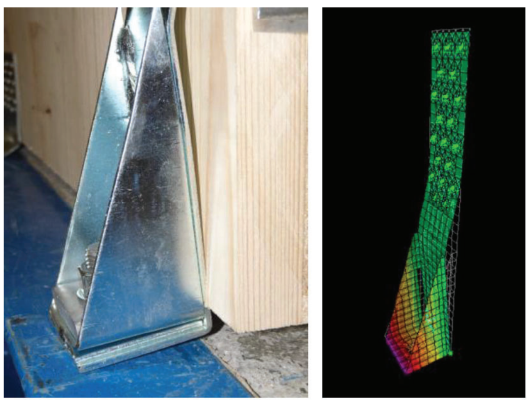

Figure 7. Hold down in CLT wall

Fig. 8 illustrates how the inclusion of anchor stiffness affects the vertical stiffness of the hold-down connection. The key findings are summarized as follows:

Fixed Base Condition (No Anchor Stiffness Considered)

When the anchor stiffness is not considered, the base of the hold-down is fixed, leading to a higher cumulative stiffness in the system. In this case, the nails alone resist the applied forces, resulting in a stiffer but potentially brittle response.

Effect of Including Anchor Stiffness

When anchor stiffness is incorporated, the capacity of the nails changes significantly. The interaction between the anchor and the nails alters the force distribution, leading to a more flexible yet potentially more ductile connection.

Influence of Higher Anchor Stiffness

As the anchor stiffness increases, the overall capacity of the hold-down connection is affected. A higher anchor stiffness allows for better force redistribution, potentially reducing stress concentrations in the nails and improving energy dissipation.

5 – CONCLUSION

The analysis demonstrates that while the inclusion of anchor hysteresis does not significantly influence the initial stiffness, it plays a crucial role in enhancing the ductility and energy dissipation capacity of the system. The presence of the anchor bolt mitigates brittle failure and promotes a more controlled deformation response, making it a vital consideration in seismic performance evaluations.

The findings also highlight the critical role of anchor stiffness in modifying the behavior of the hold-down connection. When the base is fixed (no anchor considered), the nails experience a stiffer response, which may lead to brittle failure. In contrast, incorporating anchor stiffness results in a more balanced force distribution, ultimately enhancing the overall ductility and performance of the wall under seismic loading.

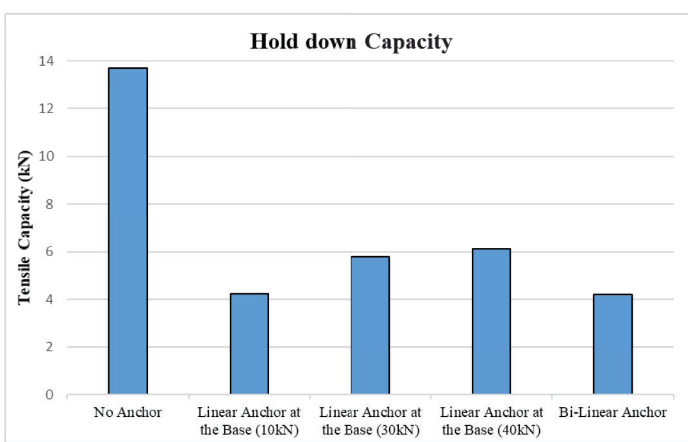

Figure 8. Effect of the anchor stiffness on the capacity

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6 – REFERENCES

[1] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, and A.Thiel. "Cross laminated timber (CLT): Overview and development." In: European Journal of Wood and Wood Products, 74(3), 331–351. (2016) https://doi.org/10.1007/s00107-015-0999-5

[2] A. Ceccotti, C. Sandhaas, M. Okabe, M. Yasumura, C. Minowa, and N. Kawai. "Seismic response of multi-storey cross-laminated timber buildings." Proceedings of the World Conference on Timber Engineering, 10–14 (2013).

[3] S. Pei, J. W. Van de Lindt, M. Popovski, J. W. Berman, J. D. Dolan, J. Ricles, & H. E. Blomgren. "Cross-laminated timber for seismic regions: Progress and challenges for research and implementation." In: Journal of Structural Engineering,145(10),04019120 (2019).https://doi.org/10.1061/(ASCE)ST.1943-541X.0002392

[4] I. Gavric, M. Fragiacomo, & A. Ceccotti. "Cyclic behavior of CLT wall systems: Experimental tests and analytical prediction models." In: Journal of Structural Engineering,141(11),04015034(2015). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001246

[5] J. Ožbolt, R. Eligehausen, G. Periškić, & U. Mayer. "3D FE analysis of anchor bolts with large embedment depths." In: Journal of Engineering Structures, 29(9), 2247–2257(2007). https://doi.org/10.1016/j.engstruct.2006.11.014

[6] K. M. A. Hossain, J. Wright, & W. Hawkins. "Nonlinear finite element analysis of anchor bolts in concrete under seismic loading." In: Journal of Engineering Structures,204,110036(2020). https://doi.org/10.1016/j.engstruct.2019.110036

[7] M. Fragiacomo, C. Amadio, & L. Macorini, "Seismic response of hybrid systems coupling cross-laminated timber panels and reinforced concrete frames." In: Journal of Structural Engineering, 140(2), 04013049 (2014). https://doi.org/10.1061/(ASCE)ST.1943-541X.0000808

[8] T. Smith, F. Ludwig, & E. Karacabeyli, "Evaluation of current design standards for CLT anchor systems under seismic loads." In: Journal of Earthquake Engineering,22(5),783–805(2018). https://doi.org/10.1080/13632469.2017.1297264

[9] E. C. Fischer, S. Pei, J. W. Van de Lindt, & M. Popovski. "Probabilistic seismic risk assessment of CLT buildings considering anchor bolt damage." In: Journal of Engineering Structures,228,111551(2021). https://doi.org/10.1016/j.engstruct.2020.111551

[10] G. C. Foliente. "Hysteresis modeling of wood joints and structural systems." In: Journal of Structural Engineering, 121(6),1013–1022(1995). https://doi.org/10.1061/(ASCE)0733-9445(1995)121:6(1013)

[11] S. G. Cho, & K. Salman. "Seismic demand estimation of electrical cabinet in nuclear power plant considering equipment-anchor interaction." In: Journal of Nuclear Engineering and Technology(2021). https://doi.org/10.1016/j.net.2021.10.021

[12] F. McKenna, G. L. Fenves, & M. H. Scott. "Open system for earthquake engineering simulation (OpenSees)." Pacific Earthquake Engineering Research Center, University of California, Berkeley (2000).

[13] A. Aloisio, F. Boggian, R. Tomasi, & M. Fragiacomo. "The role of the hold-down in the capacity model of LTF and CLT shear walls based on the experimental lateral response." In: Journal of Construction and Building Materials, 289, 123046 (2021).

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