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OUT-OF-PLANE CONSTITUTIVE MODEL TO CAPTURE THE TSUNAMI-LOAD RESPONSE OF CROSS LAMINATED TIMBER BUILDINGS

R. A. Salgado[(1)], S. Guner[(2)]

[(1)] *Ph.D. Student, University of Toledo, rafael.salgado@rockets.utoledo.edu*
[(2)] *Assistant Professor, University of Toledo, serhan.guner@utoledo.edu*

Abstract

Cross Laminated Timber (CLT) is a new and robust construction material that has gained increasing popularity as an alternative to create the resilient cities of the future. The response of CLT buildings under earthquake conditions has been widely investigated and shown to be favorable. To create disaster-resilient communities, new building systems must be able to withstand not only earthquakes but also subsequent tsunami events. Despite the good seismic performance of CLT buildings, their performance under tsunami load conditions has not yet been investigated. A valuable methodology to ensure the adequate performance of buildings under tsunami events is the performance-based engineering (PBE). To yield valid results, the PBE methodology requires an accurate numerical characterization of the system-level response of the building. However, the responses of CLT panel connections subjected to tsunami-induced out-of-plane load conditions have only started to be investigated in the literature. As a result, there is a lack of out-of-plane constitutive models for these connections – an essential requirement for an accurate system-level numerical characterization of CLT buildings under tsunami events. The objective of this study is to advance the current understanding of the tsunami-induced out-of-plane responses of CLT panel connections with the end goal of enabling the use of the PBE methodology for the determination of the tsunami performance of CLT buildings. To achieve this objective, two research tasks are undertaken. In the first task, a constitutive model is developed to simulate the tsunami-induced out-of-plane responses of two commonly used CLT panel connections. To extend the developed constitutive model to different connection design configurations, a numerical investigation with 48 high-fidelity nonlinear connection models is conducted. The results are used to create a simple equation that allows for the rapid determination of the parameters of the constitutive model as a function of various connection design configurations. In the second task, a performance-based tsunami analysis of a two-story CLT building is conducted to demonstrate how to use the developed constitutive model on a system-level scale and how it enables a more accurate determination of the tsunami performance of CLT buildings. The tsunami-induced responses of panels and connections as well as their contribution to the system response are investigated. The results showed that the developed constitutive model enabled a more accurate determination of the tsunami performance of CLT buildings including the tsunami-induced response of panels and connections, and the interactions between in- and out-of-plane resisting elements.

Keywords: CLT panel connections; constitutive model; performance-based; system-level modeling; tsunami disaster

1. Introduction

The increase in damage caused by natural disasters has necessitated the research for new building systems to create the resilient cities of the future. Cross Laminated Timber (CLT) is a relatively new and robust construction material that has received considerable attention as a promising alternative to traditional, vulnerable materials. Given that earthquakes are the most common sources of tsunamis, new building systems must exhibit adequate performance during both seismic and subsequent tsunami events. While the seismic response of CLT buildings has been extensively investigated and shown to be favorable [1-3], there is a lack of research and understating on the performance of this new material under tsunami load conditions.

Performance-based engineering (PBE) is a relatively new methodology that aims to provide a realistic and reliable understanding of the resilience of a building in potential disaster events [4,5]. In order to extend this methodology to tsunami loads, a critical requirement is to obtain an accurate representation of the building response under these events. This often relies on the availability of system-level numerical models capable of accurately characterizing the tsunami-induced structural response of CLT buildings. However, the available models have been developed for seismic load conditions, which cannot be used to fully predict the tsunami response.

Unlike seismic loads that primarily engage the in-plane response of CLT panels, a wave pressure creates a load pattern that predominantly engages the out-of-plane responses (see Fig.1). A few available studies have examined the out-of-plane response of isolated CLT panels [6-8] while not considering the influence of the panel connections. These connections are known as the "weak links" used to join the rigid and strong CLT wall panels to the CLT floor panel or to the foundation, as shown in Fig.1. They are commonly comprised of metal connectors (e.g., angle brackets), steel fasteners (e.g., nails or bolts), and the connected section of the CLT panels or foundation. Consequently, their out-of-plane responses are typically governed by certain connection design configurations, such as the number of nails on the wall and floor sides of the connection, and the wood species used in the CLT panel. The responses of CLT panel connections subjected to tsunami-induced out-of-plane load conditions have only recently started to be investigated in the literature [9]. There is still a lack of out-of-plane constitutive models for CLT panel connections – an essential requirement for an accurate system-level numerical characterization of the CLT building response under tsunami events.

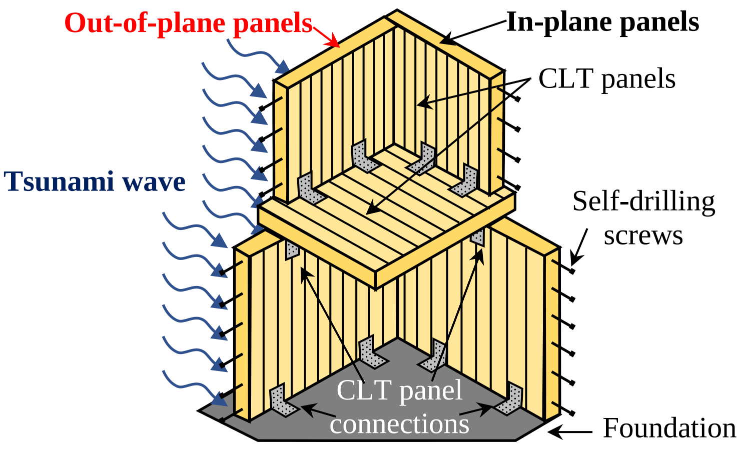

Fig. 1 – CLT building elements

The objective of this study is to advance the current understanding of the tsunami-induced out-of-plane responses of CLT panel connections with the end goal of enabling the use of the PBE methodology for the determination of the tsunami performance of CLT buildings. To achieve this objective, two tasks are undertaken. In the first task, a constitutive model is developed for the tsunami-induced out-of-plane responses of two commonly used CLT panel connections, based on key response parameters such as the elastic and plastic stiffnesses, and the yield and maximum forces. A numerical investigation with 48 high-fidelity nonlinear connection models is conducted to extend the developed constitutive model to account for the influences of different connection design configurations. A simple equation is derived to allow the rapid determination of the parameters of the constitutive model as a function of various connection design configurations. In the second task, a performance-based tsunami analysis of a two-story CLT building is conducted to demonstrate how to use the developed constitutive model on a system-level scale and how it enables a more accurate determination of the tsunami performance of CLT buildings. The results are used to investigate the tsunami-induced response of CLT panels and connections as well as their contribution to the system response. The interactions between in- and out-of-plane resisting elements, and the system-level resilience and damage levels are also investigated.

2. Tsunami-Induced Out-Of-Plane Responses of CLT Panel Connections

In this section, a brief summary of the out-of-plane responses of two commonly used CLT panel connections is presented to provide the background information needed for the constitutive model development in *Section 3*. In a prequel paper, the response of CLT panel connections subjected to tsunami-induced out-of-plane load conditions was investigated by Salgado and Guner [9]. High-fidelity nonlinear numerical models of two CLT panel connections commonly used in today's CLT buildings (see Fig.2a and Fig.2b) were developed and validated with experimental studies from the literature. The validated connection models were used to develop a fundamental understanding and characterize their response under the two out-of-plane load conditions shown in Fig.2c and Fig.2d. The first condition is representative of a tsunami load that impacts the exterior wall of the building, forcing the out-of-plane CLT panel to move towards the inside of the structure (referred to as out-of-plane exterior, or OPE). The second condition is representative of the interior pressure exerted by the tsunami inundation that has entered the building, forcing the out-of-plane CLT panel to move towards the outside of the building (referred to as out-of-plane interior, or OPI). More details on the high-fidelity nonlinear numerical model developed, experimental validation studies and detailed out-of-plane results can be found in reference [9].

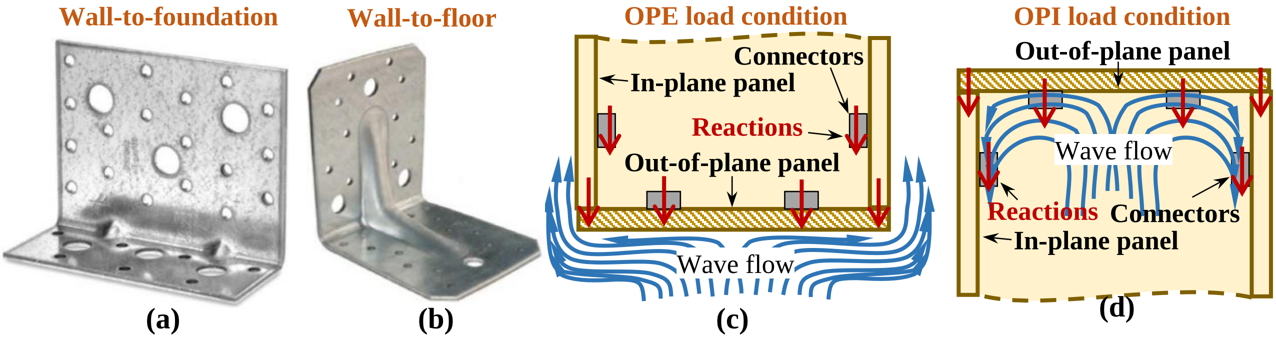

Fig. 2 – (a) Wall-to-foundation, (b) wall-to-floor connections, and (c) OPE and (d) OPI load conditions investigated [9]

When subjected to the OPE load condition, the responses of both connections are governed by the crushing of the wall panel's wood fibers onto the lower section of the angle brackets, as shown in Fig.3a and Fig.3b. The OPE load-displacement response is characterized by a stiff and linear response up to the peak load capacity followed by a favorable plastic response, as shown in Fig.3e and Fig.3f, which reflected the ductile crushing response of the wood panels. Under the OPI load condition, the responses of both connections are governed by the axial withdrawal of the nails on the wall side of the connection with no significant damage on the floor side, as shown in Fig.3c and Fig.3d. For both connections, the OPI load-displacement response is characterized by a softer pre-peak response up to the peak load capacity of the connections followed by a softening branch, as shown in Fig.3g and Fig.3h [9].

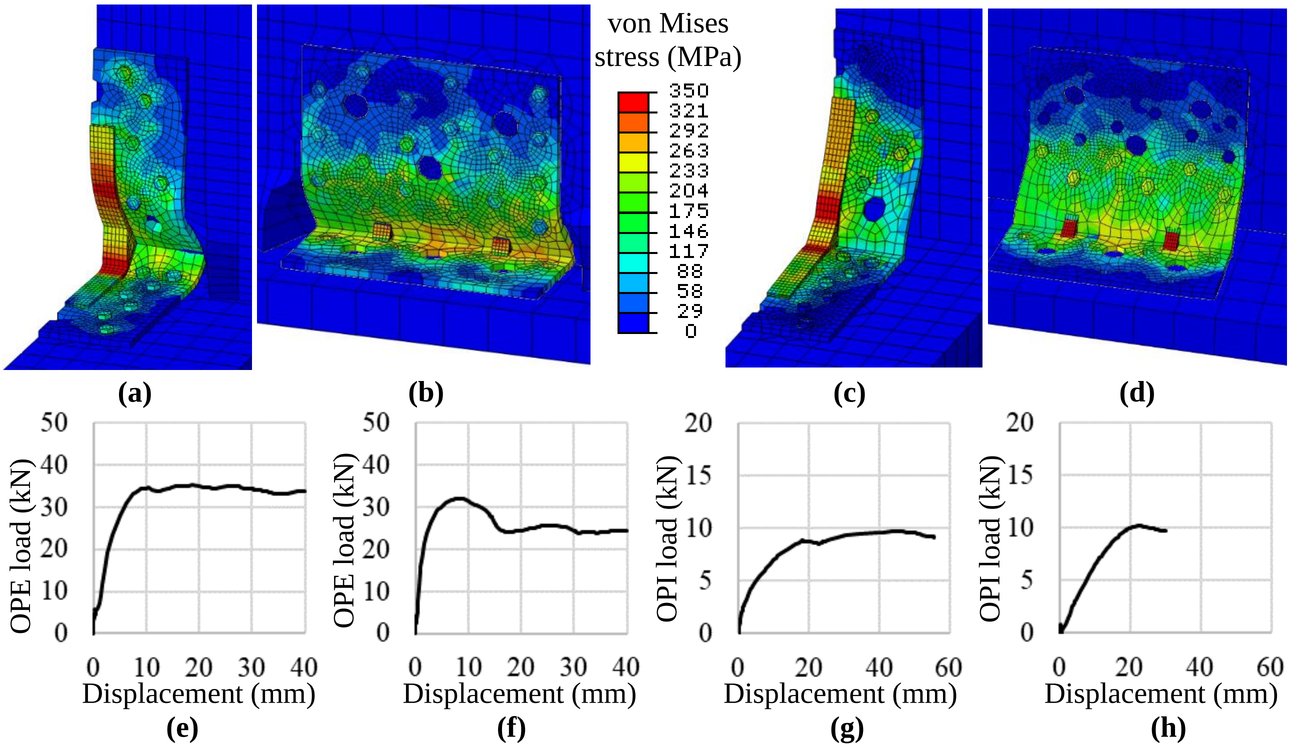

Fig. 3 – Numerical responses of the wall-to-floor and wall-to-foundation connections under (a)-(b) OPE load condition, (c)-(d) OPI load condition, and (e)-(h) associated calculated load-displacement responses [9]

3. Task 1: Out-Of-Plane Constitutive Model Development for CLT Panel Connections

The calculated tsunami-induced out-of-plane responses of the CLT panel connections discussed in *Section 2* were used to develop and calibrate a nonlinear constitutive model. The model combines the OPE and OPI responses in a single curve, with the OPE- and OPI-related parameters in the negative and positive regions, respectively, as shown in Fig.4a. In practical applications, the positive or negative region of the constitutive model should reflect the expected response of the connection. If the connection is modeled such that the positive direction of movement (i.e., in relation to the axes of the model) represents an OPE load condition, then the model parameters should have opposite signs to those shown in Fig.4a.

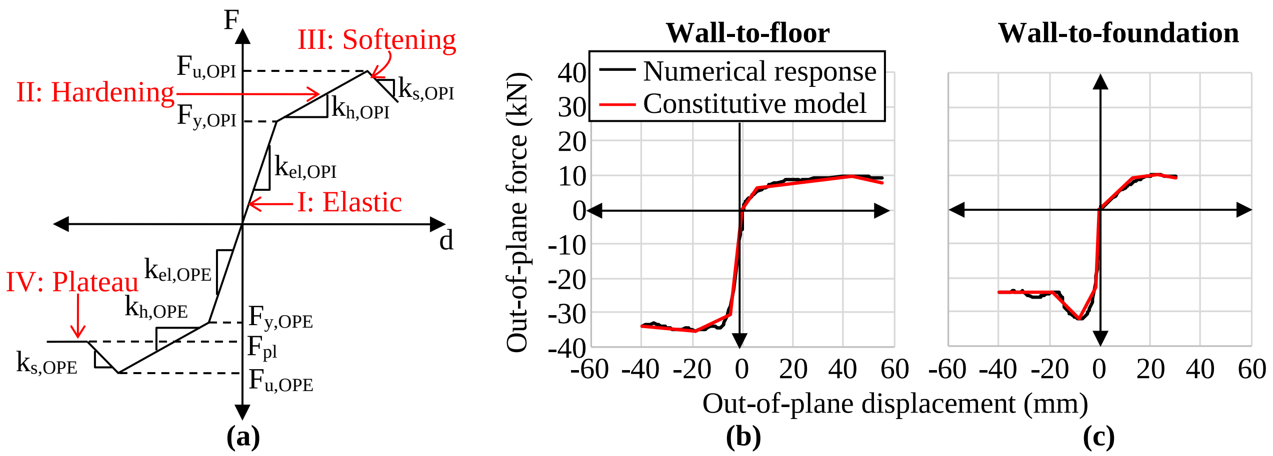

Fig. 4 – (a) Proposed constitutive model and fit of the calibrated model with the high-fidelity numerical responses for the (b) wall-to-floor and (c) wall-to-foundation connections

The constitutive model is characterized by six linear branches – three related to the OPI load condition and three related to the OPE load condition – defined by 10 model parameters, as shown in Fig.4a. Branch I models the elastic response of the connections and is defined by the elastic stiffness k_{el} and yield force F_y parameters. Branch II models the post-elastic hardening response of the connections and is defined by the hardening stiffness k_h and the ultimate force capacity F_u parameters. Branch III models the post-peak softening response and is defined by the softening stiffness k_s parameter. The OPE response of the wall-to-foundation connection constitutes a special case, in which an additional branch, Branch IV, defined by the plastic force F_{pl} parameter, accounts for the post-peak plastic response discussed in *Section 2*.

The elastic and hardening stiffnesses, as well as the yield force parameters of the constitutive model, were calculated following the method proposed in the European standard for testing of joints made with mechanical fasteners [10]. The Software for Phenomenological Implementations, So.ph.i. [11], was used to calibrate each parameter of the constitutive model using the load-displacement responses discussed in *Section 2* and shown in Fig.3e through Fig.3h. The software searches for the best trilinear approximation of the experimental results (i.e., the high-fidelity numerical analyses in this study) to minimize the difference in dissipated energies [12]. Fig.4b and Fig.4c show, respectively, the out-of-plane responses of the wall-to-floor and wall-to-foundation connections discussed in *Section 2* overlaid by the proposed model with calibrated parameters (see Table 1). It is evident from Fig.4b and Fig.4c that the constitutive model accurately captures the tsunami-induced out-of-plane responses of the CLT connections including the nonlinear and post-peak stages.

Table 1 – Calibrated parameters for the wall-to-floor and wall-to-foundation constitutive models

	Wall-to-floor							**Wall-to-foundation**					
	k_{el}	**F_y**	**k_h**	**F_u**	**k_s**	**F_{pl}**		**k_{el}**	**F_y**	**k_h**	**F_u**	**k_s**	**F_{pl}**
OPI	1.21	6.47	0.08	9.67	-0.16	-		6.60	30.43	0.33	35.13	-0.06	-
OPE	0.71	9.11	0.10	10.15	-0.15	-		16.73	22.73	1.42	32.01	-0.70	24.36

Once the constitutive model was shown to accurately capture the out-of-plane responses of CLT panel connections, a numerical investigation was conducted to expand it to connection design configurations beyond the ones analyzed in *Section 2*. The connection design configurations considered were the wood species used in the CLT panels, the number of nails in the wall side of the connection N_w, and the number of nails on the floor side of the connection N_f. The investigated levels of each connection design configuration are summarized in Fig.5. The high-fidelity nonlinear numerical models of the connections described in reference [9] were used to calculate the OPE and OPI responses of all the possible combinations of the considered connection design configurations. In total, 48 numerical analyses were performed.

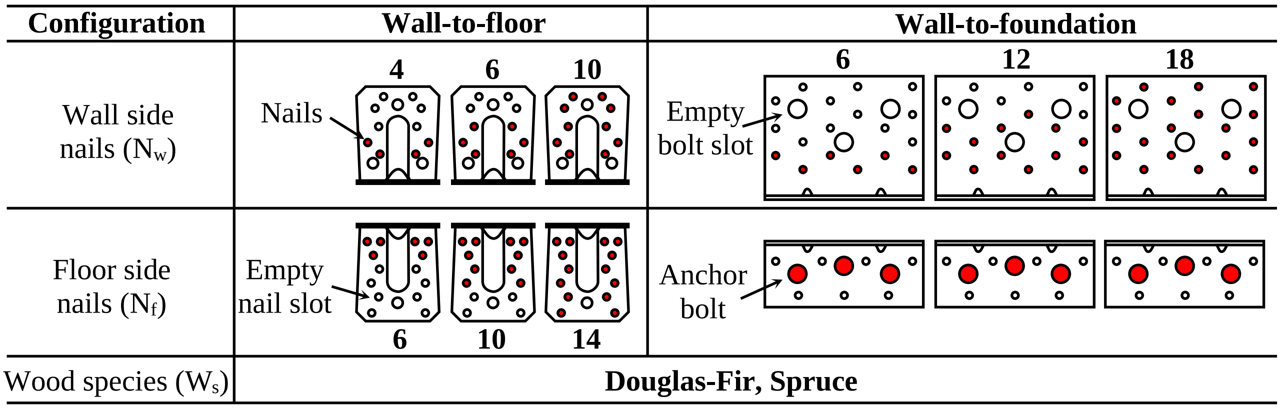

Fig. 5 – Connection design configurations considered in the numerical investigation

The load-displacement results from each of the 48 analyses were subjected to the calibration process in order to obtain the constitutive model parameters. The dataset containing the 246 calibrated parameters was statistically treated in order to fit the equation defined by Eq. (1) for each model parameter. Eq. (1) is comprised of four constant factors and is used to calculate each model parameter as a linear combination of the number of nails in the wall side N_w, and the number of nails on the floor side N_f of the connection. The fitted values of each constant factor in Eq. (1) are summarized in Table 2 together with the average errors of using the fitted equation compared to the actual calculated value of the parameters. The results indicate an excellent accuracy of the fitted model.

$$\text{Param} = C + C_{ws} + C_w N_w + (C_f N_f)^* \quad (1)$$

where C is a constant factor; C_{ws} is a constant factor based on the wood species of the CLT panel; C_w is a factor based on the number of nails in the wall side of the connection; C_f is a factor based on the number of nails in the floor side of the connection. The term $C_f N_f$ is not applicable to the wall-to-foundation connections because this connection type is typically attached to the foundation using high-strength steel bolts.

Table 2 – Values of the factors in the equation for the parameters of the constitutive models

	Wall-to-floor							Wall-to-foundation				
Row	**Param**	**C**	**C_{ws} Douglas Fir**	**C_{ws} Spruce**	**C_w**	**C_f**	***Avg Err. (%)***	**C**	**C_{ws} Douglas Fir**	**C_{ws} Spruce**	**C_w**	***Avg Err. (%)***
OPI												
1	k_{el}	0.48	-0.04	0.04	0.01	0.05	*1.1*	0.66	0.00	0.00	0.00	*0.2*
2	F_y	7.14	0.00	0.00	0.09	-0.12	*0.2*	9.78	-0.08	0.08	-0.02	*0.0*
3	k_{1p}	0.02	0.00	0.00	0.00	0.00	*2.3*	0.09	0.00	0.00	0.00	*0.7*
4	F_u	7.70	0.00	0.00	0.17	0.00	*2.3*	10.49	-0.04	0.04	-0.02	*0.0*
5	k_{2p}	-0.10	-0.01	0.01	-0.01	0.00	*5.8*	-0.31	0.02	-0.02	0.01	*1.1*
OPE												
6	k_{el}	3.17	0.54	-0.54	0.07	0.15	*1.2*	16.40	2.76	-2.76	-0.11	*0.3*
7	F_y	22.99	3.00	-3.00	0.44	0.00	*1.0*	17.87	2.36	-2.36	0.12	*0.5*
8	k_{1p}	0.90	0.06	-0.06	-0.07	0.00	*9.4*	1.20	0.14	-0.14	0.00	*0.8*
9	F_u	25.33	3.20	-3.20	0.67	0.00	*0.9*	27.98	3.61	-3.61	0.01	*0.0*
10	k_{2p}	-0.16	0.00	0.00	-0.03	0.01	*23.0*	-0.68	-0.11	0.11	0.00	*2.1*
11	F_{pl}	-	-	-	-	-	-	19.21	1.85	-1.85	0.15	*0.2*

Eq. (1) is a simple equation that allows the rapid determination of the constitutive model parameters of the two CLT panel connections as a function of the design configurations considered. For instance, to calculate the ultimate OPI force capacity parameter F_u for the wall-to-floor connection with any combination of N_f, N_w, and W_s, Eq. (1) is used with the factors given in the fourth row of Table 2. This process is then repeated for the other parameters that characterize the constitutive model. The factors in Table 2 are also good indications of which connection design configuration significantly affected the constitutive response of the connection. In fact, some of the factors were equal to zero, which indicates that the corresponding configuration did not affect the model parameter and, therefore, could be excluded from the calculation without any loss of accuracy.

4. Task 2: Performance-Based Tsunami Analysis of a Two-Story CLT Building

To demonstrate how to use the constitutive model developed in *Section 3* on a system-level scale and how it enables a more accurate determination of the tsunami performance of CLT buildings, a performance-based tsunami analysis of the two-story CLT building shown in Fig.6a is performed in this section. The building was designed for a location with high seismicity such as Blaine, USA and experimentally analyzed in Popovski and Gavric [13], the results of which are used in this study for validation purposes. This building was chosen because its seismic design and experimental results are available in the literature, which allowed for the calculated tsunami performance to be representative of a building seismically designed for the same region. Another factor that contributed to the selection of this building was its reduced size, which enabled a computationally efficient and concise analysis for the purposes of this study.

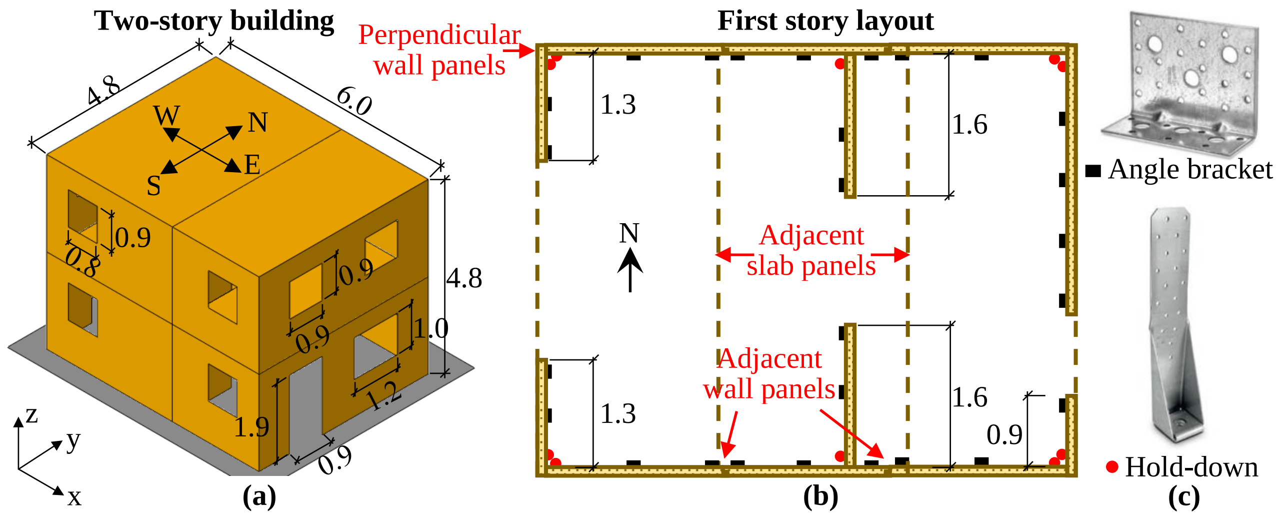

Fig. 6 – (a) Overview of the two-story CLT building, (b) first story plan [13], and (c) CLT panel connections used (dimensions in meters)

The first step of the performance-based analysis is to determine how the performance will be measured and what is the desired performance level of the building. The building performance was determined based on the calculated maximum story drift. Since the tsunami response of CLT buildings is still a novel research area, no performance levels have yet been developed. Attary et al. [14] indicated that it is acceptable to use performance levels developed for seismic conditions to estimate the tsunami performance. Thus, three levels of 1%, 2%, and 4% maximum story drifts associated with low, medium, and extensive damage were used [15].

The subsequent steps of the performance-based analysis are: i) the creation and ii) validation of a system-level model, iii) the definition of the tsunami load, and iv) the tsunami performance assessment. The performance of the building should be conducted involving a large number of structural analyses, a large suite of input tsunami loads, and analytical models with properties that have been randomly varied. For demonstration purposes and space restraints, only one tsunami intensity is considered in this study.

4.1 Creation of the system-level numerical model

The system-level numerical model created in this study is comprised of CLT panels and CLT panel connections. A simplified modeling approach was used to reduce the computational cost associated with the numerical modeling of large structures. As such, the CLT panels were modeled using 4-node, 6-degree-of-freedom shell elements, and the CLT panel connections were modeled using 2-node, 3-degree-of-freedom connector elements (i.e., springs), as shown in Fig.7a and Fig.7c, respectively.

The CLT walls and slabs of the building (see Fig.6b) are made of three layers of Spruce wood with a total thickness of 94 mm. Fig.6b shows only the layout of the first story of the building; for more details, the reader is referred to reference [13]. A composite layup approach was used with the shell elements to account for the orthogonal material directions of each layer of the CLT panels, as shown in Fig.7b. The wood constitutive response was characterized as orthotropic elastic with brittle failure.

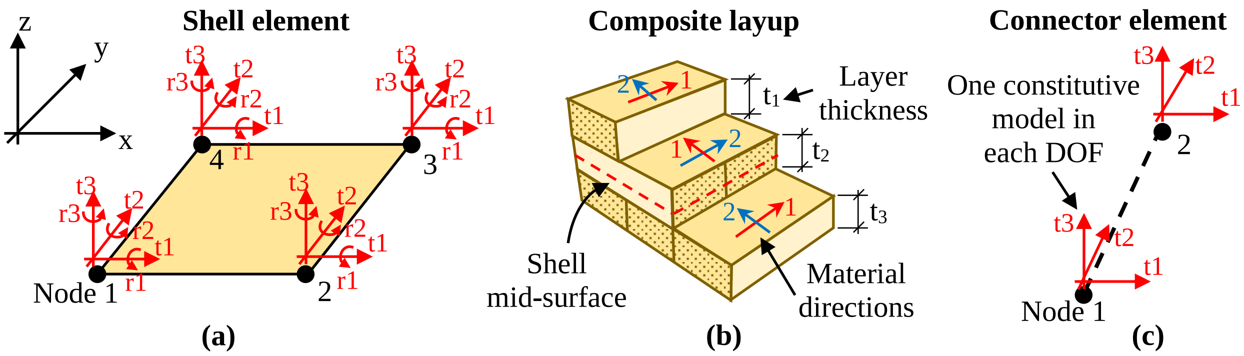

Fig. 7 – (a) Shell element, its (b) composite layup, and (c) connector element

The second and first stories of the building are connected, respectively, to the first story and the foundation using the connector elements. These elements were modeled using three uncoupled constitutive models – one for each degree-of-freedom – to simulate the axial, in-plane, and out-of-plane responses of the CLT panel connections shown in Fig.6b and Fig.6c. The model developed in *Section 3* was used for the out-of-plane constitutive model while references [12,16] were used for the axial and in-plane responses. In the experimentally tested building, the angle bracket shown in Fig.6c was used as both wall-to-foundation and wall-to-floor connections in the first and second stories, respectively. As a wall-to-foundation connection, six nails were used in the wall side of the connection (i.e., $N_w = 6$) while as a wall-to-floor connection, four nails were used in the wall side (i.e., $N_w = 4$) and three screws were used in the floor side. For the wall-to-floor connections, the number of nails on the floor side of the connection N_f was taken as the maximum available (i.e., 14 nails) to simulate the stronger screws used in the actual connection. The out-of-plane constitutive model parameters of the connections were calculated using Eq. (1) and Table 2.

The hold-down connections shown in Fig.6c are responsible for providing the uplift resistance. Their out-of-plane responses were assumed as a linear elastic response with stiffness equal to their in-plane shear response. This assumption was used in previous CLT building models [17] and should not result in significant loss of accuracy in out-of-plane load conditions because the hold-downs are located very close to the in-plane resisting CLT walls (see Fig.6b). Consequently, at these locations, the responses of the in-plane elements dictate the response of the out-of-plane panels.

As discussed in *Section 3*, the OPE and OPI regions of the constitutive model should reflect the expected response of the connection. For the building considered, the connections on the south side had the OPE region at the positive y-axis and the OPI region at the negative y-axis (see axes on Fig.6a). The connections on the east side of the building had the OPE region at the negative x-axis and the OPI region at the positive x-axis. The connections at the north and west sides of the building had the opposite signs to the south and east connections, respectively.

A fixed, rigid plane was created to represent the foundation and simulate its interaction with the wall panels. For validation purposes, the experimentally imposed monotonically increasing load applied on each story of the east wall towards the west direction was employed in the numerical model. An inverted triangular pattern with the top load twice as much as the bottom load was used [13], as shown in Fig.8a.

4.2 Validation of the system-level numerical model

Fig.8a shows the stress condition in the CLT building subjected to the experimentally imposed lateral loads. At the maximum applied load level, Popovski and Gavric [13] reported a large sliding of the first story and no significant damage to the CLT panels. This response was successfully captured by the numerical model. The panel connections of the in-plane walls (i.e., in relation to the load direction) of the south and north walls of the first story failed, as shown in Fig.8a. In addition, the calculated CLT panels' stresses were approximately 30% of their ultimate limits, which matches the experimental observation of no significant damage.

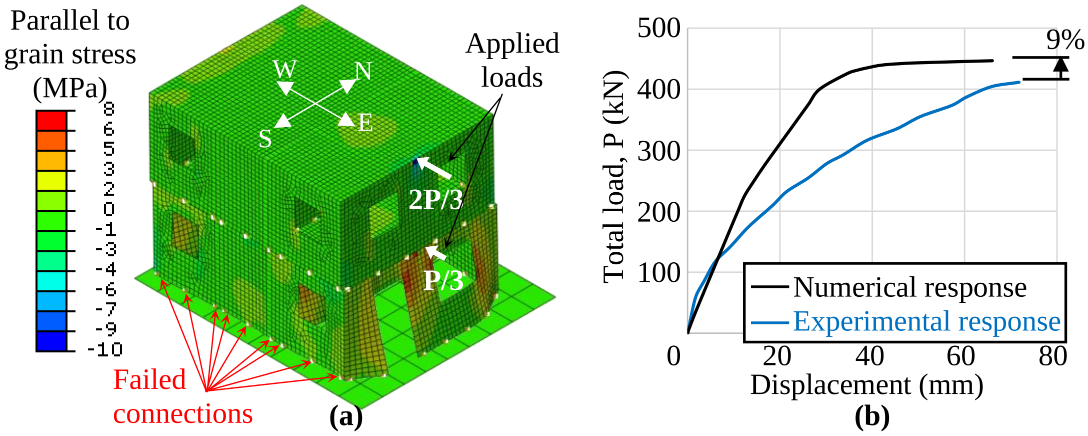

Fig. 8 – (a) CLT building at failure condition (10x displacement scale) and its (b) load-deflection response

Fig.8b shows the load-displacement response of the system-level numerical model. The peak load capacity of the building was accurately calculated with a reasonable 9% overestimation. The calculated response exhibited an initial stiffness similar to the experimentally observed one. In the subsequent softening stage, the calculated response overestimated the stiffness, which can be attributed to the higher experimental flexibilities of the panel-to-panel connections. These connections, which typically use self-drilling screws, were not considered in the created model. A fixed condition was assumed between the perpendicular and adjacent wall panels, and between adjacent slab panels (see the location of these connections in Fig.6b). Experimental evidence supports the rigid behavior of the connections between adjacent slab panels and perpendicular wall panels; however, the assumption of rigid connections between in-plane wall panels generally results in a model stiffer than the actual structure [18,19]. This can be considered on the safe side since the real structure actually possesses greater ductility than the numerical model and its response will be more favorable (i.e., more ductile) than that predicted by the numerical analysis [20].

4.3 Definition of the tsunami load

After the validation of the model, the tsunami load was applied on the south wall towards the north direction, where the building possessed the least number of openings (see Fig.6a). This allowed the tsunami load to better engage the building. At the building location, the inundation depth and flow velocity were calculated to be 2.30 m (a little short of the first story height of 2.34 m) and 4.3 m/s^2, respectively, using the energy grade line analysis method [21].

An equivalent uniform pressure was applied to the CLT building up to the calculated inundation depth. This pressure is statically equivalent to the tsunami impulsive load, which occurs when the leading edge of the tsunami surge of water impacts the building. After this initial impact, the load degrades to the hydrodynamic load, which is the load imposed on an object by water flowing against and around it at moderate to high velocities. Consequently, the impulsive load was calculated with an amplification factor of the hydrodynamic load given in Eq. (2) from the ASCE7 standards, Clause 6.10.2.1 [21].

$$F_{imp} = \alpha(1/2)\rho_s C_d B C_{cx}(hu^2) \tag{2}$$

where α is the impulsive load amplification factor with a maximum value of 1.5 [14]; ρ_s is the fluid density including sediment (taken as 1,200 kg/m^3); C_d is the drag coefficient given in ASCE7 [21]; B is the breadth of the building plane normal to the direction of the flow; C_{cx} is a coefficient that accounts for the openings in the building; h is the inundation depth; and u is the flow velocity.

4.4 Tsunami performance assessment

With the validated system-level model and the defined tsunami load, the tsunami performance of the two-story CLT building was assessed to determine if the considered maximum story drift performance levels were met, or exceeded, at the considered load level. Fig.9a shows the system-level total load-top story displacement response of the building. Approximately 90% of the building displacement was concentrated in the first story. The maximum calculated drift was 0.7% for the first story and 0.04% for the second story. Consequently, the tsunami performance of the building remained below the first performance level considered of 1% (see Fig.9a). The other performance levels do not appear in Fig.9a as they would require a displacement beyond 40 mm. The following discussion presents the details of the building response and demonstrates how an out-of-plane constitutive model for the CLT panel connections such as that developed in *Section 3* enables a more accurate determination of the tsunami performance of CLT buildings.

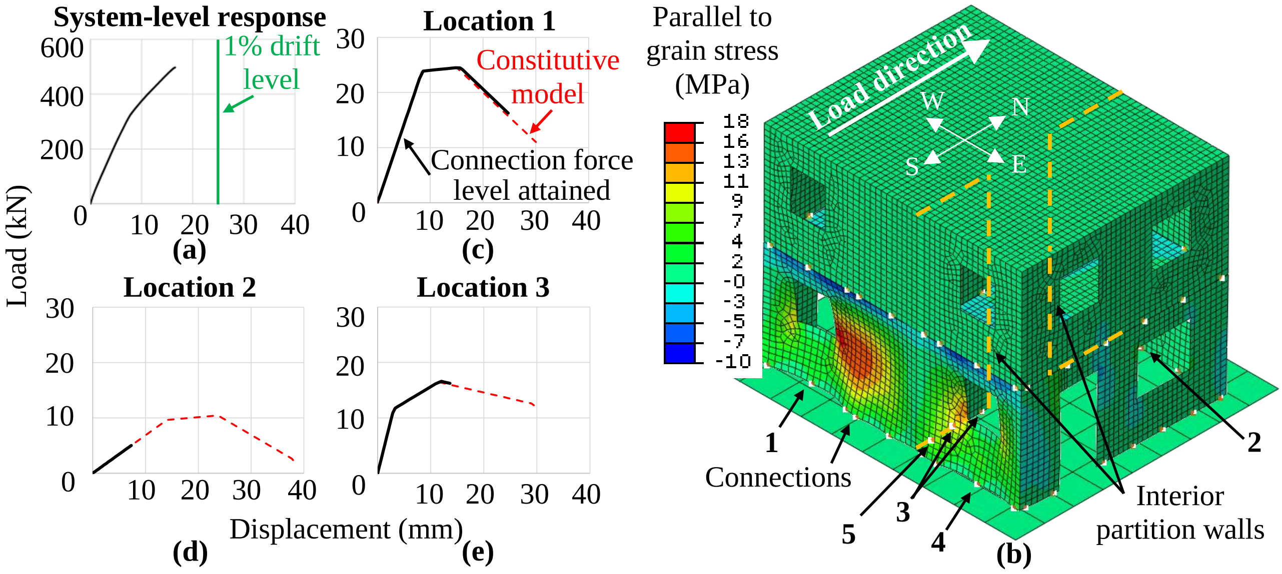

Fig. 9 – (a) Load-second story displacement response of the building, (b) CLT building at tsunami load condition (10x displacement scale), (c)-(e) the load-deflection response of selected connections

Fig.9b shows that the building was able to resist the imposed tsunami load with no damage to the CLT panels. The stresses on the CLT panels were concentrated on the south side of the building and were well below the panel strengths of 72 MPa in tension and -39 MPa in compression. The stresses in the perpendicular direction of the CLT panels remained within ±2 MPa (not shown in Fig.9b), which were also well below the panel strengths of 10 MPa in tension and -5 MPa in compression. Since the inundation depth was smaller than the height of the first story, the second story of the building experienced insignificant stresses.

Only one of the out-of-plane resisting connections on the south side of the building (see Location 1 in Fig.9b) reached its maximum force resistance. This is shown in Figure 9c, which presents the ideal load-displacement response of the connection defined by the constitutive model and the force level attained as the result of the tsunami load imposed on the structure. The other out-of-plane resisting connections reached force levels within 90% of their maximum force resistance. The connections farther away from the in-plane resisting elements were subjected to the highest out-of-plane loads. For instance, the connection at Location 4 (see Fig.9b) reached a force level of 99.6% of its maximum force resistance. The connections on the north side of the building (see Location 2 in Fig.9b as an example), which were subjected to an OPI load condition, experienced force levels well within their elastic limits, at approximately 50% of the yield force, as shown in Fig.9d. On the north side, the connections closer to the in-plane resisting elements were subjected to the highest out-of-plane loads, which is the opposite of the response of the south side connections. This occurred because, on the north side, the in-plane walls were the elements that impose the OPI loads on the out-of-plane wall panels. For the in-plane loaded connections, only the two angle brackets at Location 3 in Fig.9b reached their maximum shear force capacity, as shown in Fig.9e. On the other hand, no hold-downs exceeded their maximum capacity, with the one subjected to the highest in-plane shear force (shown at Location 5 in Fig.9b) experiencing force levels of 85% of its capacity.

Based on the calculated response and the results discussed in this section, it can be concluded that the building performed well to the tsunami load considered, with minimal damage to the CLT panels and connections. The response resulted in a building performance below the "low damage" level, which indicates that it could resist tsunami loads beyond the one considered herein. The adequate response of the out-of-plane resisting elements – the determination of which was made possible by the developed out-of-plane constitutive model – allowed an effective redistribution of the tsunami loads to the in-plane load resisting elements.

5. Conclusions

The results of this study support the following conclusions:

- An out-of-plane constitutive model was developed based on six linear branches and ten model parameters. The calibrated model accurately captured the nonlinear and post-peak tsunami-induced out-of-plane responses of the CLT panel connections.
- A simple equation was created based on a dataset of 246 calibrated model parameters to allow the rapid determination of the parameters of the constitutive model as a function of various connection design configurations. The average error between the fitted equation and the actual calculated values was within 5% for most of the model parameters, indicating excellent accuracy.
- The use of the developed out-of-plane constitutive model on the system-level tsunami analysis revealed that, when subjected to OPE load condition, the connections subjected to the highest out-of-plane loads were farther away from the in-plane load resisting elements. On the other hand, when subjected to OPI load condition, the connections subjected to the highest out-of-plane loads were closer to the in-plane load resisting elements.
- The performance-based analysis conducted demonstrated that the use of the developed constitutive model enabled a more accurate determination of the tsunami performance of CLT buildings including the tsunami-induced response of CLT panels and connections, and the interactions between in- and out-of-plane resisting elements.
- The performance-based analysis also revealed that the interaction between the in- and out-of-plane load resisting elements was crucial for the adequate tsunami performance of CLT buildings due to their role in the tsunami load redistribution throughout the building.

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