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COLLAPSE FRAGILITY OF A 5-STORY CLT STRUCTURE UNDER CHILEAN SUBDUCTION EARTHQUAKE RECORDS

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ABSTRACT: Mass timber structures have been utilized in North America, Europe, and Oceania, and are being evaluated in Latin America to decrease the housing shortage and the construction industry's contribution to greenhouse gas emissions. In Chile, where seismic activity is common, it is crucial to provide resilient timber structures that safeguard life safety and reduce earthquake-induced damage and repair costs. The Performance-Based Earthquake Engineering (PBEE) framework offers a practical alternative for designing more efficient timber buildings and assessing the risks related to seismic hazards, potential damage, and economic losses. In this paper, the PBEE framework is employed to assess the likelihood of a government-subsidized 5-story cross-laminated timber building collapsing under seismic stress in Chile. The probabilistic seismic hazard analysis (PSHA) was used for hazard site characterization, and the collapse probability analysis indicated a probability of less than 0.1% for a building with the mentioned characteristic, making it suitable for construction in Chile. Further research is required to achieve loss estimation under the PBEE framework, such as quantifying damage fragility curves of representative engineering details for Chilean construction.

KEYWORDS: PBEE, CLT, PSHA, Conditional Mean Spectrum, Record Selection, Collapse

1 INTRODUCTION

Cross-laminated timber (CLT) is a mass timber product increasingly used in the construction of mid-rise and high-rise buildings, as an alternative to the traditional materials like concrete, steel, and masonry [2]. The usual constructive system in CLT buildings is the platform type, it consists of walls and slabs composed of solid timber panels with high stiffness and strength in their plane, attached through metal brackets and fasteners [3]. In these constructions, the floor panels are supported by the walls of the lower story, therefore the walls are interrupted at each level [4] and the main source of energy dissipation comes from the wall-to-wall parallel connections and overturning restraint system (i.e. hold-downs) as it is illustrated in Figure 1 [5].

In Chile, cross-laminated timber is a scarcely used product, unlike Europe and North America, where midrise and high-rise buildings have been built using CLT panels as the main material for walls and floor diaphragms [6-8]. However, recent studies [9-12] seek to promote the use of the CLT platform system using radiata pine grown in Chile as raw material by proposing design recommendations such as seismic performance factors (i.e., seismic response modification factor R = 2.0 and inter-story drift limit of 0.2%) and design procedures that are waiting for its incorporation in national design codes. Considering the high seismicity of the country and the lack of formal code-based recommendations, it is essential to provide resilient timber structures where structural and non-structural components adequately protect life safety and reduce earthquake-induced damage and repair costs. In this context, Performance-Based Earthquake Engineering (PBEE) becomes a convenient alternative when the structure's critical elements (CLT-to-CLT connections) exhibit non-linear behaviour, allowing for the design of more efficient buildings and assessing the risk associated with the seismic hazards, potential damage, and economical losses according to the location where they are built. In this paper, the PBEE framework will be employed to assess the probability of collapse of a government-subsidized 5-story cross-laminated timber building designed under the Chilean seismic design code considering the proposed seismic performance factors developed in [11].

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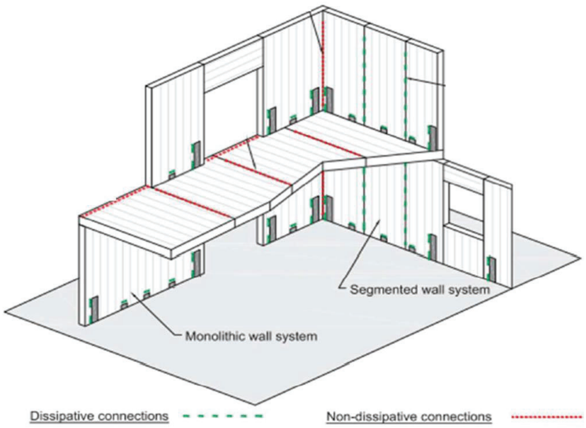

Figure 1*: Schematics of a CLT structure (platform system) with the indication of the dissipative and non-dissipative connections (taken from [5]).*

2 BUILDING DESCRIPTION

It is important to clarify that the building being studied is still in the project stage. It was defined based on the criteria for government-subsidized housing in Chile, taking into consideration the specific needs and requirements of the target population. The projected building has five floors with a height of 2.6 m each. The length, width, and height of the building are 20.55 m, 7.05 m, and 10.4 m, respectively, with floors and walls made of 3-ply CLT (i.e., 120mm of thickness), using Chilean radiata pine as raw material, with two apartments in each level (55 m^2 per apartment). The building structure has been designed with monolithic wall as a lateral system with hold-downs and shear keys as overturning and sliding restraint systems, respectively. The staircase that provides access to the apartments is located in the middle. It was assumed that the building will be built on a typical soil type in the city of Santiago (i.e., Vs30 > 350 m/sec). The archetype of the building is illustrated in Figure 2. Figure 3 shows corresponding panels in a red box on the floor plan (a) to indicate the panel distribution on the elevations (b).

3 NUMERICAL MODELING

In order to evaluate the response of the building, two modeling variants were considered to illustrate the impact of considering a simplified 2D approach and the possible system effect on the response of the 3D structure. These are (i) a representative 2D planar elevation of the structure (i.e., A-A axis), and (ii) a full 3D representation of the building structure. Both numerical models were developed on OpenSeesPy [13]. Shell elements (i.e. shellMITC4 element) with isotropic material were used for the CLT walls panels and nonlinear springs (i.e. zeroLength element) were used for the hold-downs and shear keys (see Figure 4) as according to [5] both connection are responsible for the energy dissipation in the monolithic wall system. The wall-to-wall perpendicular connection was considered non-dissipative and perfectly rigid. The test data reported in [10] on full-scale CLT shear walls and in [14] on hold-downs and shear keys were considered for the calibration of the numerical model. The modeling and calibration procedure described in [12] was used as a base for the development of the input parameters (i.e., elastic parameters for shell elements and SAWS constitutive parameters for the zeroLength elements) models. Based on previous numerical studies [15], the floor and the roof were modelled as rigid diaphragms with mass lumped at each story.

Figure 2: *Building considered: (a) typical floor plan, (b) exterior longitudinal elevation, (c) inside longitudinal elevation, and (d) transverse elevation. All dimensions in millimeter.*

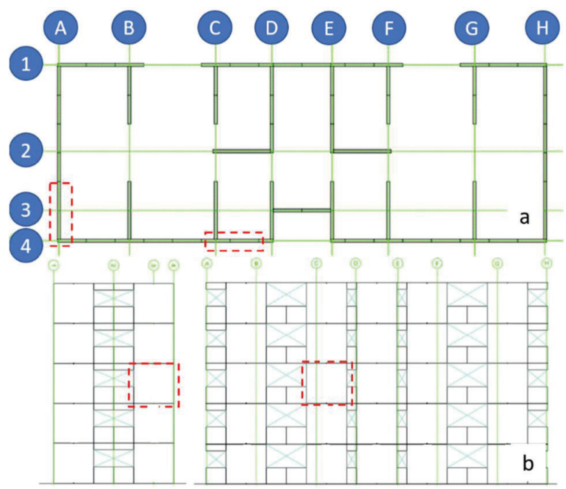

Figure 3: *CLT shear wall distribution in (a) plan and (b) elevation (along A-A and 1-1).*

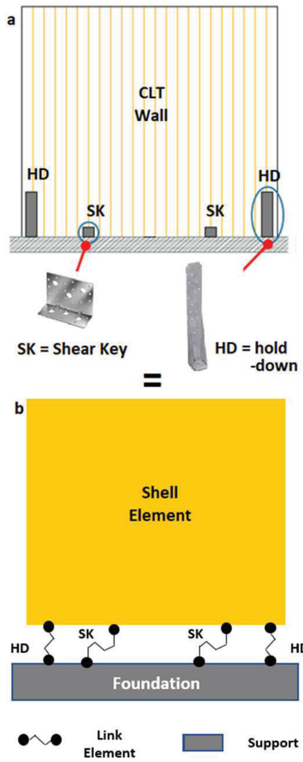

Figure 4: *(a) Typical CLT shear wall configuration used in the building, (b) schematic of FE model for CLT shear walls.*

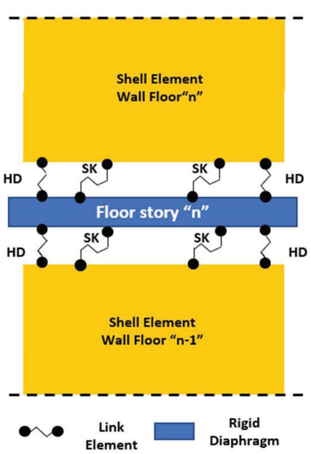

Figure 5: *Schematic of FE model for CLT shear walls at the story "n"*

For the 2D structure, the first fundamental period of the nonlinear structural model was determined as 0.515 sec. For the 3D building model, the first fundamental periods of the nonlinear building model at both translational directions were determined as 0.292 sec and 0.257 sec. The first mode is predominately in the X direction and the second mode is in the Y direction.

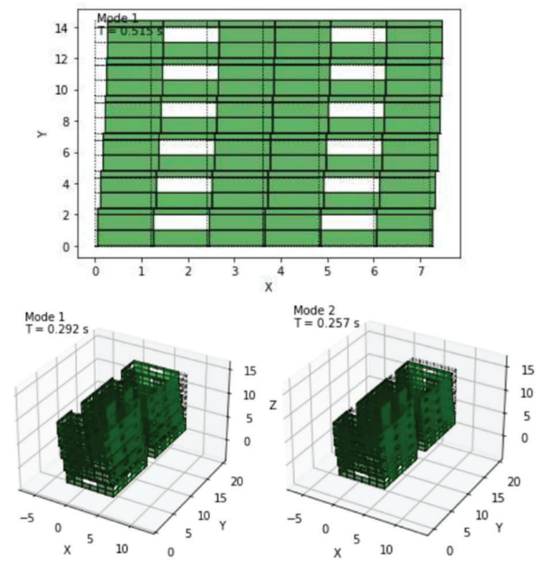

Figure 6: *Mode shape of the structure for (top) 2D simplified model and (bottom) 3D model.*

4 SEISMIC HAZARD

Chile is located in a highly seismic-prone area. Megathrust earthquakes are mainly attributable to the subduction of the Nazca plate beneath the continental South American plate. This subductive interaction is considered the only source of earthquake hazard to perform nonlinear time history analysis (NLTHA) and Multiple Stripe Analysis (MSA).

A probabilistic seismic hazard analysis (PSHA) was conducted to compute the seismic hazard associated with the site location of the building. For the development of the PSHA, the recurrence model developed in [16] and the Ground-motion prediction equation (GMPE) for the Chilean subduction zone developed in [17] were used. An example of the seismic deaggregation for the site of the building is presented in Figure 4 considering a return period of 4975 years (a 1% probability of exceedance in 50 years) at the spectral acceleration of the building period.

Table 1: *Deaggregation results.*

Mean Scenario	*Period (sec)*		
	0.515	*0.292*	*0.257*
Magnitude	*7.80*	*7.83*	*7.83*
Distance (km)	*135.2*	*147.3*	*145.8*

Ground motion (GM) records from the SIBER-RISK database were selected to match the target Conditional Mean Spectrum (CMS) on the period of interest considering the procedure developed in [18] and a maximum scale factor (SF) of 2.0. Figure 5 shows the response spectra of all selected motions adjusted to the CMS. Some of the selected records are summarized in Table 2.

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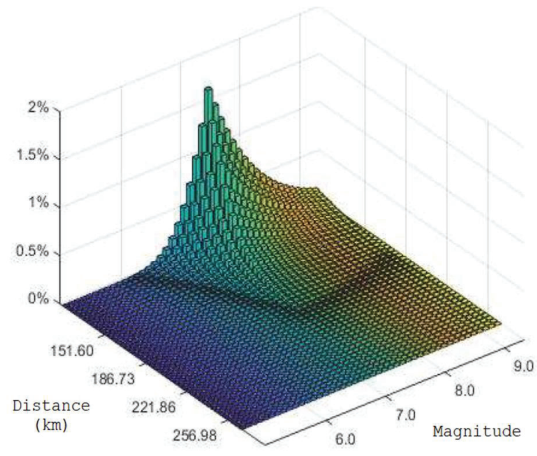

Figure 4: *Deaggregation for the considered site associated with the first mode of the 3D structure.*

In Figure 5, the conditioned spectra for both the 2D and 3D models are shown. Although these are different due to obvious reasons, such as the bidirectional quality for the 3D model, the records that fit these spectra turn out to be virtually the same. This is mainly due to the unique characteristics of the building, such as its stiffness and the parameters established, such as the selected return period.

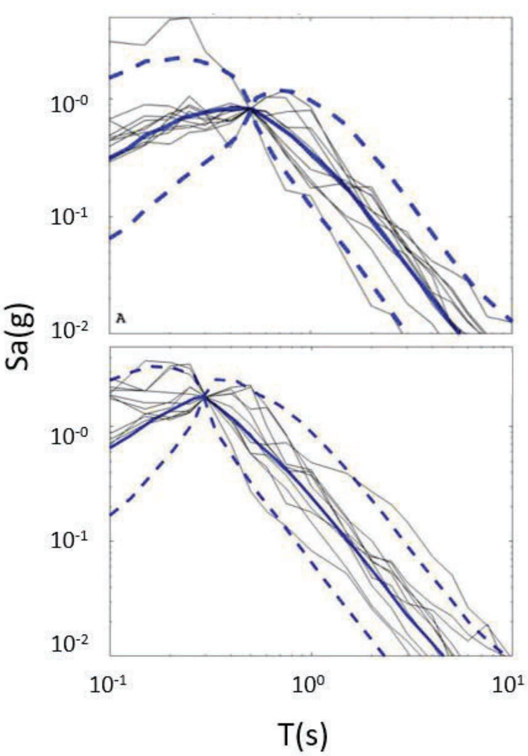

Figure 5 *Response spectra of selected motions matched to the target spectrum for (top) 2D simplified model and (bottom) 3D building model.*

Table 2: *Information on the selected ground motions.*

Location	*Year*	*Mw*	*Distance (km)*	*Station*
Quillota	*2014*	*6.4*	*54.92*	*V18A*
Algarrobo	*1985*	*7.9*	*46.92*	*MAUL06S*
Coquimbo	*2015*	*6.3*	*99.82*	*C11O*
Algarrobo	*1985*	*7.9*	*36.70*	*VALP11S*
Coquimbo	*2015*	*8.2*	*46.31*	*C11O*
Iquique	*2014*	*8.2*	*65.97*	*T10A*
Tarapacá	*2005*	*7.9*	*110.72*	*PICA*
Alto Hospicio	*2014*	*7.6*	*56.58*	*T10A*
Algarrobo	*1985*	*7.9*	*98.77*	*RANC02S*
Coquimbo	*2015*	*8.4*	*49.87*	*C23O*
Maule	*2010*	*7.9*	*50.13*	*ANGOL*

5 RESULTS AND DISCUSSION

The Multiple Stripe Analysis (MSA) method was used for evaluate the structure fragility as is illustrated in Figure 6 and 7. As expected from any structure that is subjected to earthquake loads, major forces are found at the base of the structure. In this model case, base shear keys are the ones that present the biggest internal forces and displacements due to assuming spring-like supports instead of fixed or pinned supports, making these elements the ones that dissipate more energy during a seismic event. For the model developed in this study, an improvement proposal could be to consider different connections at the base than on higher floors or tension rods to prevent the exceeding of the collapse drift limit.

In Figure 8 and 9, the collapse fragility curves for the 2D simplified model and the 3D model shows that the 2D model collapses for lower IM levels in comparison to the 3D full scale model. The collapse fragility function is computed assuming that collapse observations are independent and fit into a binomial distribution, given that a record can either cause collapse of the structure or not.

The collapse margin ratio (CMR) is an important output from the MSA, defined as the ratio between median collapse capacity and the maximum considered earthquake intensity in the Chilean code (i.e., 2% in 50 years) SMT:

$$CMR = \frac{S_{CT}}{S_{MT}} \quad (1)$$

For the 2D simplified case SMT = 0.92g whereas for the 3D building model SMT = 1.35g. Then, the computed CMR is 3.8 and 2.45 for the 2D simplified case and 3D building model case, respectively. Shahnewaz et al. (2020) estimated the CMR for a 4-story CLT building as 2.78-3.55 at collapse drift ranging from 5% to 10% considering a 2% in 50 years scenario for Vancouver. Based on the results, the simplified 2D numerical model tends to underestimate the CMR making it a not good representation of the response of the building. Having said that, this approximation could be a good estimation for buildings with a symmetric distribution of the structural components.

For the analysed structure and hazard scenario, the collapse probability is 0.5% and less than 0.1% for the 2D and 3D numerical models of the structure, respectively. This is mainly attributable to the strict design requirements of the Chilean seismic design code (i.e., mainly the inter-story drift limit of 0.2% for reduced seismic forces in an elastic design approach.

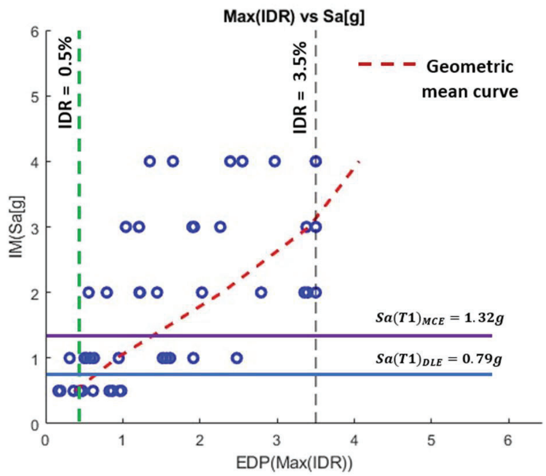

Figure 6: *MSA curves of all ground motions for the 2D simplified structure.*

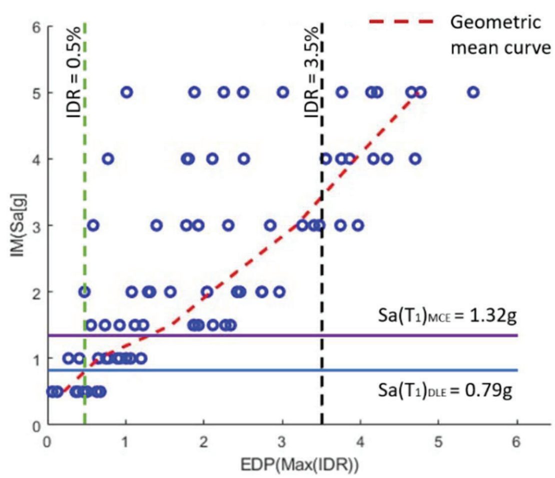

Figure 7: *MSA curves of all ground motions for the 3D building model.*

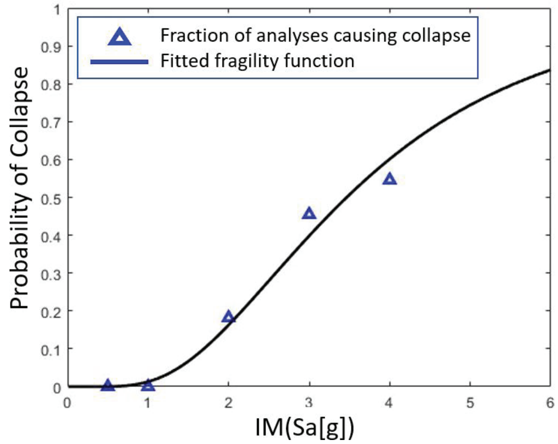

Figure 8*: Fragility curve for collapse for the 2D simplified case.*

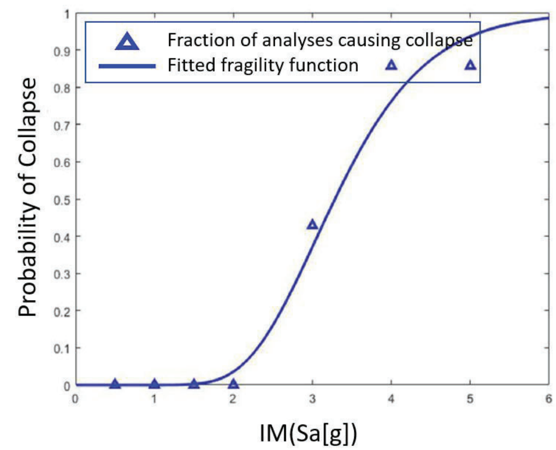

Figure 9: *Fragility curve for collapse for the 3D building mode.*

6 CONCLUSIONS

In summary, the Performance-Based Earthquake Engineering (PBEE) framework can offer a practical approach to designing resilient mass timber structures capable of withstanding seismic activity in highly prone areas such as Chile. The analysis of the collapse probability of a 5-story cross-laminated timber (CLT) building designed under Chilean seismic design code indicated a low probability of less than 0.1%, which suggests that CLT structures could be safely constructed in Chile. The simplified 2D axis has a different structural behaviour in relation to the same axis from the 3D model. From this, it can be concluded that the 2D model may not be a good representation of the behaviour of a full CLT structure given that it collapses to lower IM levels in comparison to the 3D full scale model.

Further research is necessary to improve the PBEE analysis and to obtain damage fragility curves associated with demand parameters such as inter-story drift (IDR) for structural and non-structural elements associated with CLT building design. To add depth and achieve a full

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representation of the energy dissipated by the model, it can also be considered the perpendicular wall-to-wall connection in possible iterations of the analysis. To better estimate the effects from damage and the economic loss produced, it is necessary to develop fragility curves for typical structural connections used in timber buildings.

Non-structural components, such as MEP and fire protection installations should also be considered in a more complete risk assessment analysis, which adds more variables to the damage and economic loss estimation for a type of building that requires to manage the uncertainty of using technologies that have not been mass used before in the region, in the scale that it is proposed for future development of the timber industry in Chile. Thus, opening more opportunities for research through public-private partnership in design stages and building specifications for tall timber structures, making it possible to define the pros and cons of building in CLT and other timber engineered products and innovative construction materials.

It is also important to remember that in this present study, only the maximum values of IDR independent of its direction and location have been presented. Therefore, it would eventually be of interest to establish a more detailed description of these variables to better understand the behaviour of mid-rise buildings constructed using CLT. This is necessary for estimating economic losses and providing a full probabilistic risk assessment, which would enhance decision-making support for designers, investors, and stakeholders. Regardless, the use of mass timber structures in construction presents a promising method to reduce the housing deficit and greenhouse gas emissions while ensuring building safety and resilience in earthquake-prone regions.

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