Chapitre 3

Post-Tensioned CLT Wall Systems with Multiple Rocking Segments

3.1 Résumé

Cette section présente le deuxième article présenté à la conférence "International Network on Timber Engineering Research" rédigé en collaboration avec Alessandro Palermo et Francesco Sarti de l'Université de Canterbury en Nouvelle-Zélande ainsi qu'Alexander Salenikovich de l'Université Laval. Cet article présente les considérations de conception pour le cas d'un bâtiment de 11 étages situé à Vancouver au Canada. Le SRFS est constitué de murs à sections basculantes multiples Pres-Lam en CLT.

3.2 Introduction

Due to major earthquakes that inflicted significant damage to cities around the world, thus rendering many buildings unusable and unrepairable, the seismic design codes are moving towards a low-damage philosophy (Priestley, et al., 1999 ; Naeim & Kelly, 1999 ; Palermo, et al., 2004). The interest in tall timber buildings has been growing in the last decade as a more environmentally friendly choice than concrete and steel. For timber to be a viable alternative, further research needs to be done, especially on low-damage lateral-force-resisting systems. Previous research on the Pre-Stressed Laminated (Pres-Lam) system (Palermo, et al., 2005) proposed for mass timber walls as an adaptation of the PREcast Seismic Structural System (PRESSS) (Priestley, 1991) has shown promising results when used with Laminated Veneer Lumber (LVL) in low-rise buildings. Since multi-storey timber buildings and Cross-Laminated Timber (CLT) are gaining popularity all over the world, further research is needed on the application of CLT Pres-Lam systems to mid-rise timber buildings.

As timber is a more flexible material than concrete, multi-storey timber buildings are more susceptible to a dynamic amplification of the seismic forces. In the original con-figuration, Pres-Lam walls had a single rocking interface at the wall base allowing the formation of a plastic hinge at the base. Recent research on multiple rocking segment systems in concrete buildings (Wiebe & Christopoulos, 2009) showed that by introducing connections at construction joints that allow a gap opening, the dynamic amplification effects, i.e., additional bending moments due to higher modes, can be reduced. At the same time, the need for expensive over-strength connections at construction joints is eliminated resulting in simple cost effective connections.

The first objective of this project is to demonstrate the reduction of the dynamic amplification of forces and moments in CLT multiple rocking segment systems in comparison with single rocking segment systems evaluated in previous research (Sanscartier Pilon, et al., 2017). The second objective is to develop the design procedure for the Pres-Lam system with multiple rocking segments using an 11-storey case study CLT building in Canada. Additional attention is put on the design of the connections that allow a gap opening at construction joints. To achieve these goals, non-linear numerical models of the wall segments with multi-spring elements were developed and calibrated using pushover analyses to match the analytical models. Then, a selection of strong-motion earthquakes was used to perform non-linear time history analyses (NLTHA) on the calibrated models to analyze the behavior of single and multiple rock-ing segment systems.

3.3 Single and Multiple Rocking Segments Comparison

3.3.1 Concepts

Like the PRESSS technology, the Pres-Lam uses a combination of pre-stressed steel bars designed to remain elastic inside the mass timber wall and replaceable yielding steel dissipaters positioned at the bottom corners of the walls, thus providing recentering and energy dissipation to the system. So far, single rocking segment systems have been developed and analyzed assuming rigid connections between the panels, resulting in a dynamic amplification of the forces in the upper storeys and higher costs related to the fabrication and installation (Figure 3.1(a)). Previous research demonstrated through numerical modeling that this amplification can be reduced by introducing simple connections allowing a gap opening at the construction joints, which will lead to a more flexible structure and cost savings. (Figure 3.1(b)).

3.3.2 Case Study Buildings and Seismic Analysis

To perform the analysis with the objective to demonstrate the reduction of the dynamic amplification of forces and moments by comparing CLT single and multiple rocking segment systems, several case study buildings were used (Sarti, 2015). Eight configurations of the office buildings with variable number of storeys and inter-storey heights, while having the same plan geometry, were considered (Figure 3.2). The lateral force-resisting systems consisted of post-tensioned mass timber walls with single and multiple rocking segments. A Displacement-Based Design (DBD) procedure (Priestley, et al., 2007) was performed for each case study building to obtain the design base shear (V_b) and the design base moment (M_b). The study parameters and results are presented in Table 3.1.

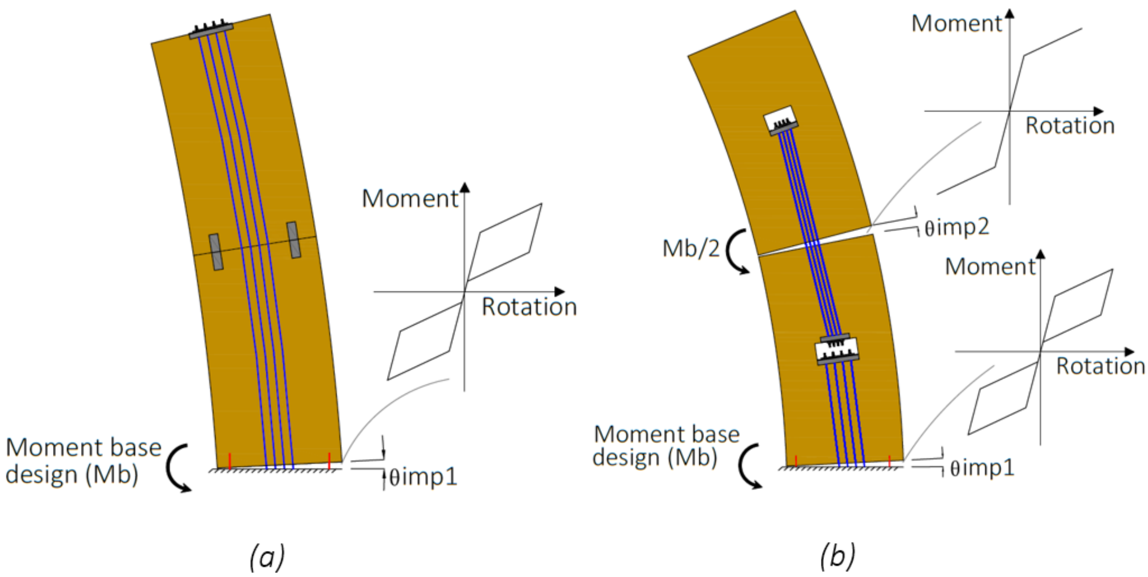

FIGURE 3.1 – Schematic systems representations : (a) Single rocking segment, and (b) Multiple rocking segments

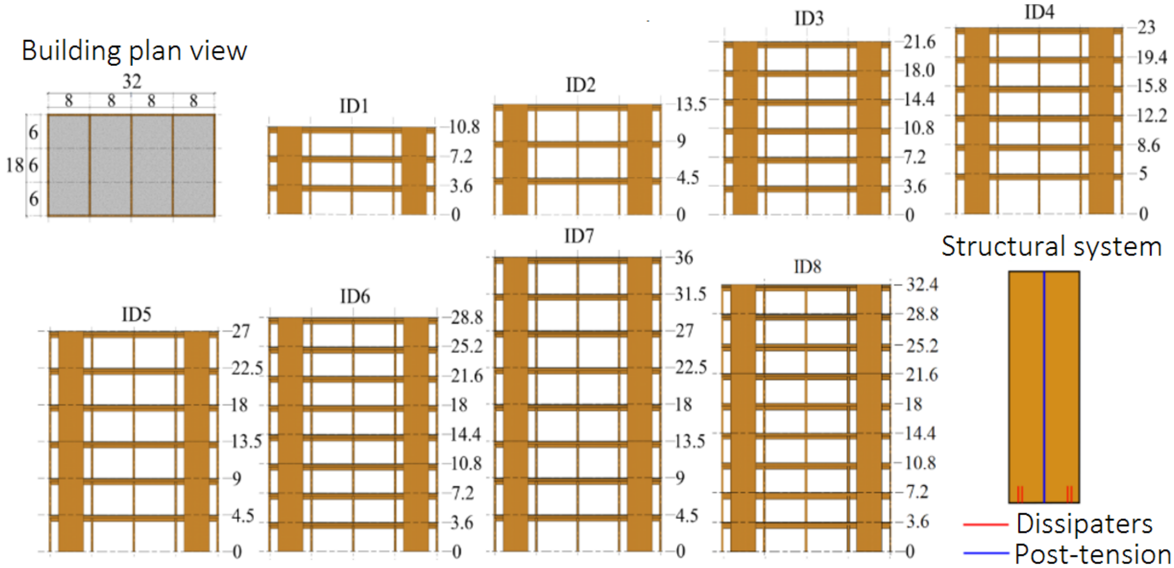

FIGURE 3.2 – Case study buildings

TABLE 3.1 – Design seismic loads

ID	No. of Storeys	h1 (m)	hi (m)	H (m)	Storey Mass (Ton)	V_b (kN)	M_b (kNm)
1	3	3.6	3.6	10.8	320	3946	33146
2	3	4.5	4.5	13.5	320	3475	36488
3	6	3.6	3.6	21.6	320	5128	79997
4	6	5	3.6	23	320	4979	83149
5	6	4.5	4.5	27	320	4108	80106
6	8	3.6	3.6	28.8	320	5148	105019
7	8	4.5	4.5	36	320	4118	105009
8	9	3.6	3.6	32.4	320	5682	130400

3.3.3 Analysis comparisons

Analytical Study

An analytical study has been performed on CLT single and multiple rocking segment systems to compare sizes of panels, post-tensioning bars and dissipaters needed to resist the design base shear and design base moment of the case study buildings. The Modified Monolithic Beam Analogy (MMBA) (Pampanin, et al., 2001) (Newcombe, et al., 2008) was used to perform the analytical study and to obtain the preliminary design pre-sented in Table 3.2 (only case study building 8 is shown).

The multiple rocking segment system was designed to reduce the load demand on the structure due to the dynamic amplification observed in the single rocking segment system design. As presented in Figure 3.1(b), the cross-section areas of post-tensioning bars are reduced at the upper segments due to less pre-stress forces and the dissipaters are only used at the base. These reductions of materials in the multiple rocking segment system allow reduction of constructions costs.

TABLE 3.2 – Case study building 8 - Single and multiple rocking segments design

Wall segment storey	Wall length (m)	Wall thickness (m)	P_t size (mm)	P_t force (kN)	Dissipater size (mm)
Single rocking segment					
1 to 9	7.2	0.314	2 Ø60	3465	4 Ø50
Multiple rocking segments					
1 to 3	7.2	0.314	2 Ø70	2694	4 Ø50
4 to 6	7.2	0.314	2 Ø55	1710	-
7 to 9	7.2	0.314	2 Ø40	634	-

Modelling and calibration

To compare the seismic forces induced in the single and multiple rocking segment systems and to demonstrate the effects of the dynamic amplification in the upper levels, non-linear time history analyses (NLTHA) were performed on numerical models. The multi-spring numerical models have been developed in OpenSEES (MecKenna, 2011). The model shown on Figure 3.3, presents an overview of the parallel zero-length multi-spring model used to simulate the contact between the base of the wall and the foundation as well as the rocking motion. The post-tensioning bars and external tension-compression yielding dissipaters were modelled as truss elements. The numerical models were calibrated by comparing the resulting curve from the pushover analysis of the numerical and the analytical studies. Multi-spring elements were added in the upper levels to model the multi-ple rocking segment systems.

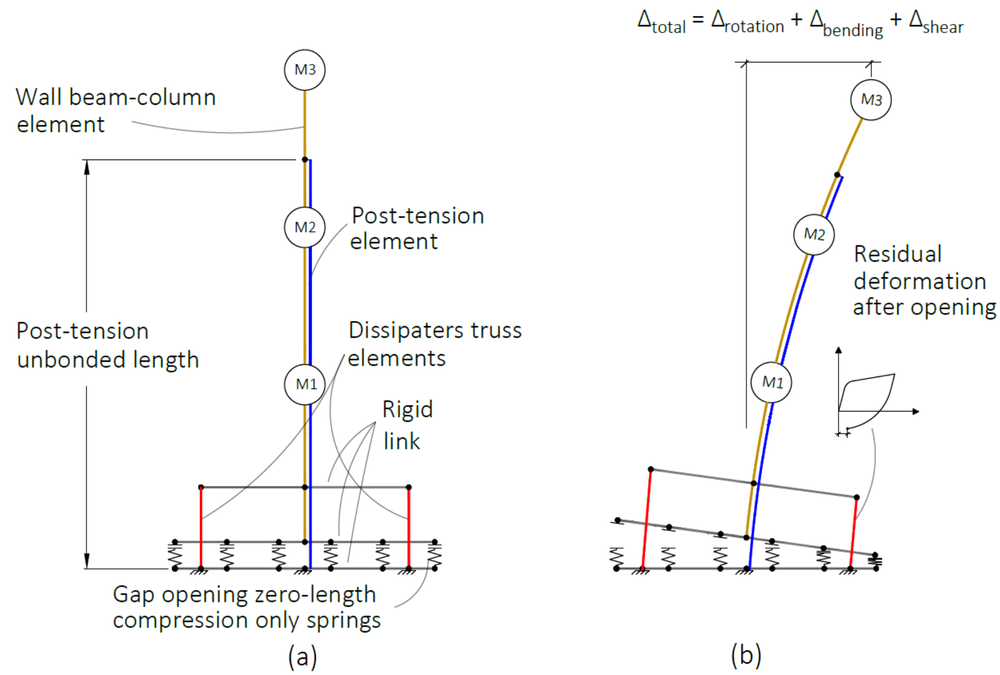

FIGURE 3.3 – Single wall multi-spring model overview : (a) initial state, and (b) deformed state

NLTHA results (building 8)

To compare the shear envelope, the bending moment envelope and the storey drift presented as the average peak storey drift to the building height of single and multiple rocking segment systems, the numerical models were subjected to NLTHA, which consisted of ten ground motion records calibrated and selected from the Pacific Earthquake Engineering Research Center (PEER) Next-Generation Attenuation (NGA) database (Chiou, et al., 2008). The spectral acceleration of each ground motion records was scaled to match the design spectrum around the fundamental period of the building. Figure 3.4 shows a list of the chosen earthquakes and the mean scaled records spectra compared to the design spectrum.

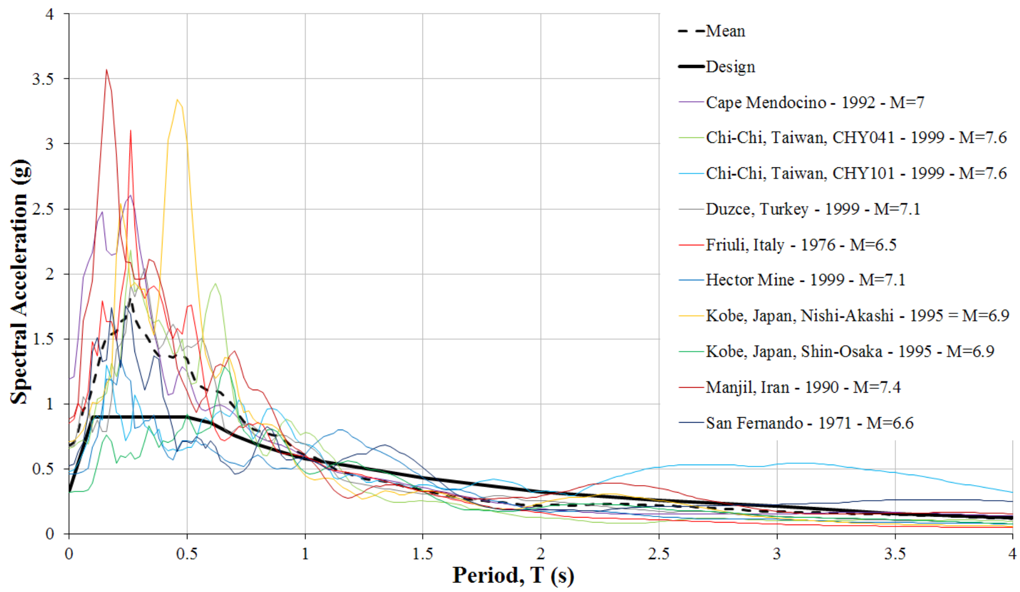

FIGURE 3.4 – Mean scaled records spectra compared to design spectrum of case study building 5 (scaled at T=1.18s)

The resulting curves in Figure 3.5, show that the single rocking segment systems are strongly marked by an effect of dynamic amplification in the upper levels, whereas the multiple rocking segment system envelopes show a significant reduction of that effect.

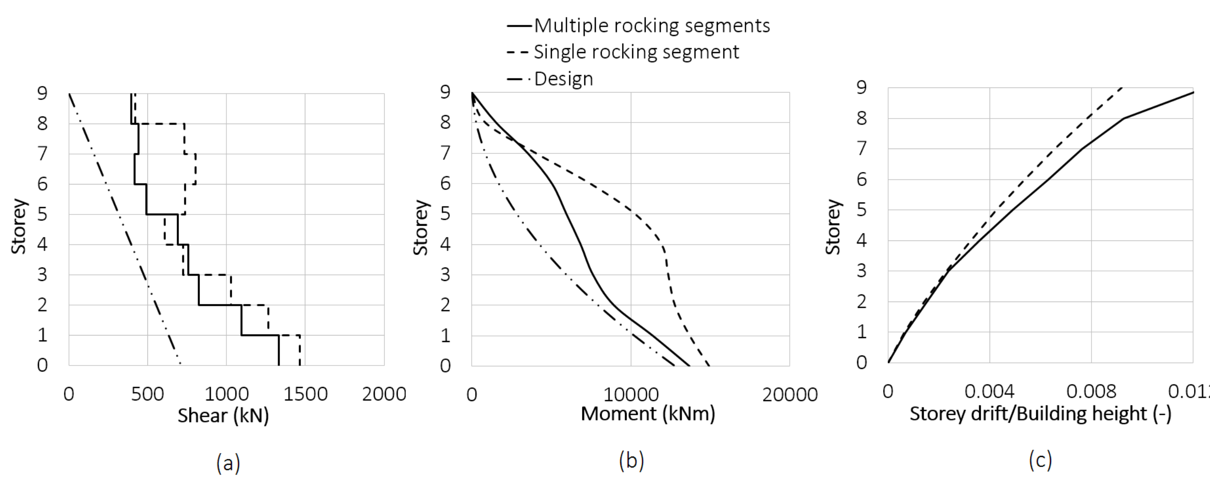

FIGURE 3.5 – Case study building 8 - NLTHA and design results for single and multiple rocking segments : (a) Shear envelope, (b) Bending moment envelope, and (c) Average peak drift (scaled at T=1.18s)

3.4 CLT Multiple Rocking Segments Case Study Building in Canada

3.4.1 Case Study Building

A complete seismic analysis and design of an 11-storey timber building located in Vancouver was performed using CLT multiple rocking segments. Each storey of the residential building has the same plan of 47.8 m long by 18.8 m wide at its maximum (Figure 3.6) with an inter-storey height of 3 m and a total height of 34.6 m. The gravity system consists of glulam timber posts and beams with CLT floors. It was designed for load combinations with snow loads and wind loads in accordance with the National Building Code of Canada (NRCC, 2015) and the CSA O86 (CSA, 2009). Results of the calculations showed that the wind loads would not govern the lateral-force-resisting system design. Seismic loads of 485-tons at each floor were considered for the DBD performed to determine the design base shear (V_b) and moment (M_b). The lateral-force-resisting system consists of 6 walls in X-direction and 7 walls in Y-direction. The length of walls in X-direction is 6.3 m, walls M1Y, M2Y, M6Y, M7Y are 7.3 m and walls M3Y to M5Y are 2.44 m. This paper presents, the DBD procedure, the analytical study, the modelling considerations, the NLTHA and an example of a con-nection detailing.

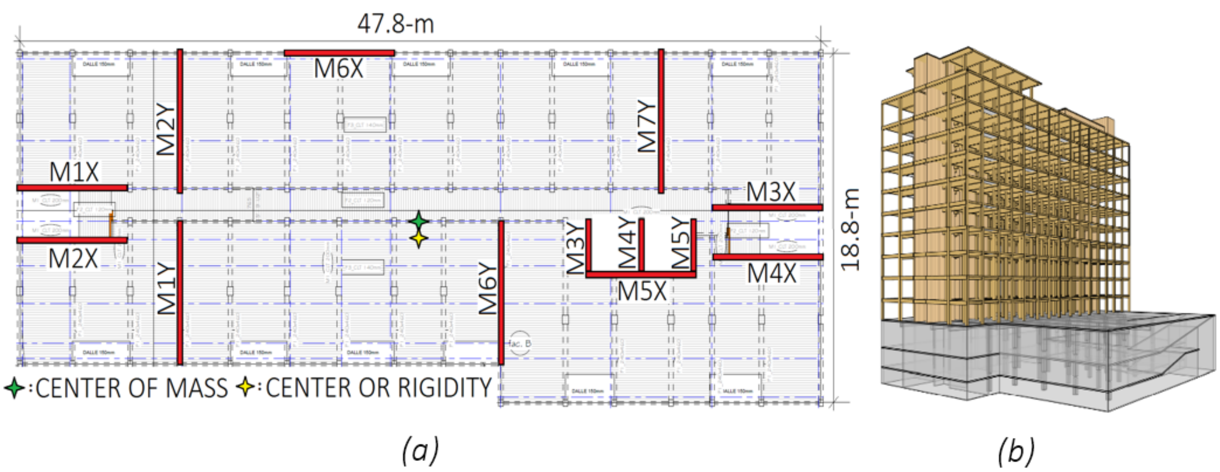

FIGURE 3.6 – Case study building : (a) Plan view, and (b) 3D view)

3.4.2 Displacement-Based Design Analysis

The DBD procedure is based on Priestley (2007). Figure 3.7(a) presents the Vancouver design acceleration spectra (NRCC, 2015) and (b) the design displacement spectra calculated based on Priestley (2007) and used to obtain the effective period of the structure (T_e). The results of the DBD analysis are presented in Table 3.3. To evaluate T_e, the design displacement (Δ_d) was selected based on code drift limits and calculated following Sarti (2015) recommendations. In the preliminary design phase, the design base shear (V_b) and design base moment (M_b), considering P-delta effects, are distributed equally among each wall of the same length. The torsion effects are being treated in the model and in the final design phases.

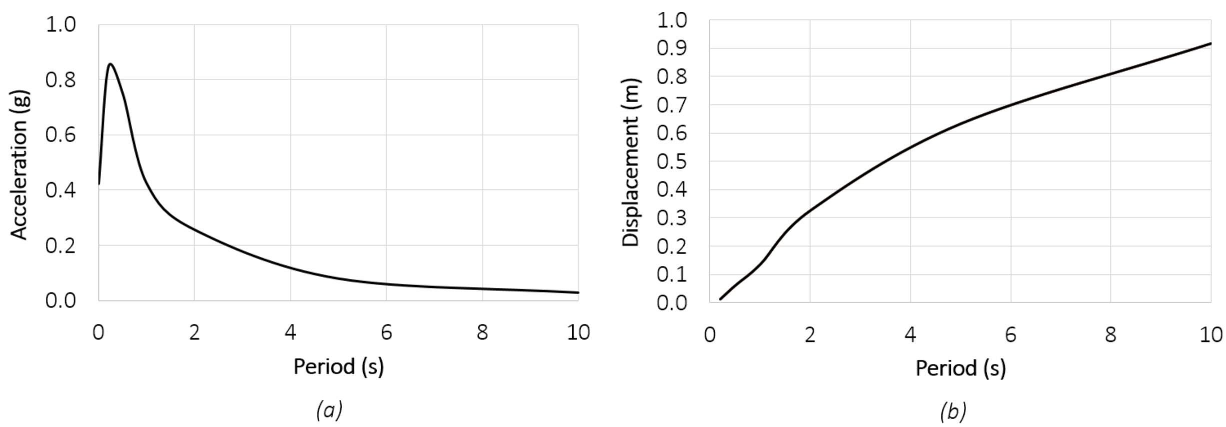

FIGURE 3.7 – (a) Design acceleration spectra, and (b) Design displacement spectra

TABLE 3.3 – Displacement-based design results

Parameters	**Symbols**	**Units**	**Values**
Design displacement	Δ_d	m	0.523
Effective height	H_e	m	21.9
Effective mass	m_e	Ton	3930
Equivalent viscous damping	ξ	%	9.33
Reduction factor for ξ	R_ξ	-	0.79
Effective period	T_e	s	3.76
Secant stiffness	K_e	kN/m	10964
Design base shear	V_b	kN	5735
Design base moment	M_b	kNm	145976

3.4.3 Analytical Study

The analytical study, or preliminary design of the walls, was performed in accordance to the Modified Monolithic Beam Analogy (MMBA). Table 3.4 presents only the design results for wall M1X in X-Direction and for walls M1Y, M3Y in Y-Direction. The preliminary design of walls M2X to M6X is the same as for wall M1X ; walls M2Y, M6Y, M7Y are the same as M1Y, and walls M4Y, M5Y are the same as wall M3Y. The results show the reduction of the wall cross sections, post-tension rod diameter and post-tension forces in the upper segments, thus lowering the costs of the lateral-force-resisting system in comparison to a single rocking segment system.

Table 3.4 – Multiple rocking segments design

Wall segment storey	Wall length (m)	Wall thickness (m)	P_t size (mm)	P_t force (kN)	Dissipater size (mm)
X-Direction - M1X					
1 to 3	6.3	0.314	4 Ø55	3905	4 Ø30
4 to 6	5	0.314	4 Ø55	5912	-
7 to 9	4.5	0.314	4 Ø50	4452	-
10 to 11	3.8	0.314	4 Ø40	2660	-
Y-Direction - M1Y					
1 to 3	7.3	0.314	4 Ø60	3616	4 Ø35
4 to 6	6.5	0.314	4 Ø55	5266	-
7 to 10	5.5	0.314	4 Ø50	5481	-
Y-Direction - M3Y					
1 to 3	2.44	0.314	2 Ø65	4837	4 Ø25
4 to 6	2.44	0.314	2 Ø60	3442	-
7 to 10	2.44	0.314	2 Ø50	2585	-

3.4.4 Modelling

To perform the NLTHA analyses and to complete the final design by considering the torsion effects of the entire building, non-linear 3D multi-spring numerical models were built and calibrated in OpenSEES (MecKenna, 2011). Multi-spring elements were added in upper levels to model the multiple rocking segment systems and all levels were attached to the mass located at the centre of mass. The analysis revealed that the shift between the centre of rigidity and the centre of mass was negligeable ; therefore, the hypothesis that walls of the same length and rigidity are subjected to the same forces and moment is valid. To compare the behaviour of single and multiple rocking segment systems, numerical models of the building using a separately designed single rocking segment system were built and subjected to the same NLTHA.

3.4.5 NLTHA Results

To observe the shear envelope, the bending moment envelope and the average peak drift of single and multiple rocking segment systems, the numerical models were subjected to NLTHA, which consisted of the same ground motion selected in section 2.3.3. Figure 3.8 presents the resulting envelopes of the wall M1X in X-Direction for single and multiple rocking segment systems. The shapes of the envelopes show a significant reduction in the shear forces and bending moments in the multiple rocking segment system. In storeys 2 to 6, the bending moments in the walls are reduced by nearly 50%. It also can be noted that whilst reducing an important part of the dynamic amplifications, there is still some residual effect in the upper storeys due to the increased flexibility of a timber building structure made of multiple rocking segments. The story drift curves show that, naturally, the multiple rocking segment system is more flexible. Nevertheless, it stayed within the drift limits prescribed by the code.

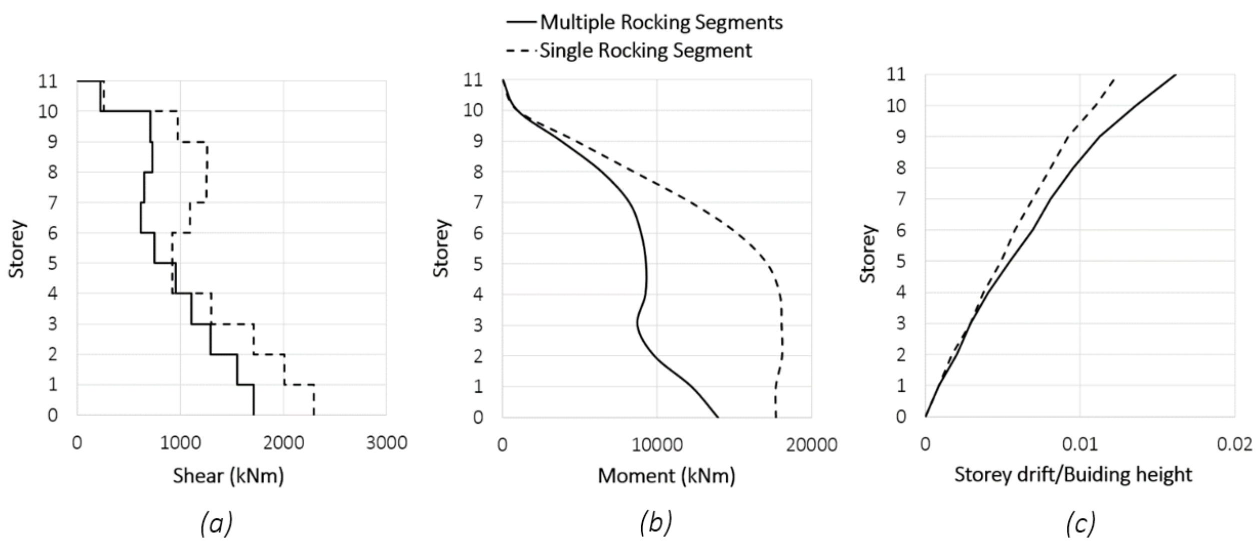

FIGURE 3.8 – NLTHA results for wall M1X : (a) Shear envelope, (b) Bending moment envelope, and (c) Average peak drift

Figure 3.9 presents the resulting envelopes for the wall M1Y in Y-Direction for single and multiple rocking segment systems. The shapes of the envelopes also show a significant reduction in the shear forces and bending moments for the multiple rocking segment sys-tem. Story drifts in Y-Direction are also within the code drift limits.

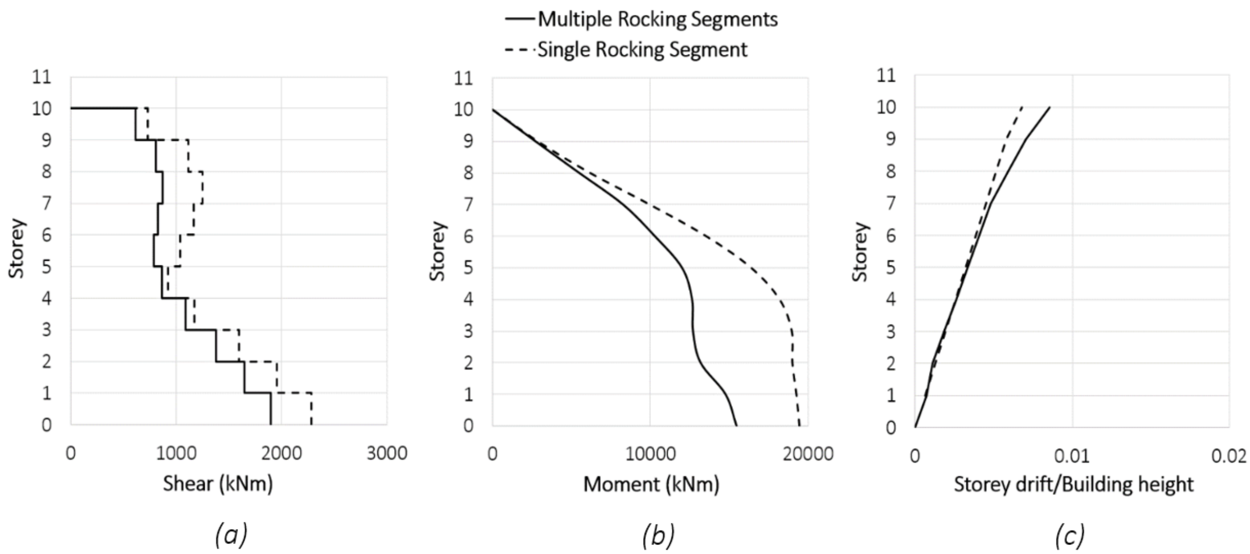

FIGURE 3.9 – NLTHA results for wall M1Y : (a) Shear envelope, (b) Bending moment envelope, and (c) Average peak drift

3.4.6 Connection design example

It is important to design the connections between the panels of the multiple rocking segment systems properly to avoid localized damage during seismic events. Figure 3.10 presents details of the connection design for wall M1X between segments 3 and 4. The post-tensioning bars are attached to a C-channel with nuts, and steel washer plates are installed in an opening cut in the wall panel. The C-channel is designed to resist the maximum bending moment developed under a uniformly distributed load resulting from the contact with the timber-bearing surface and the force in the post-tensioning bars. The area of the C-channel is determined to satisfy the following condition $0.4\sigma_r \geq \sigma_f$, where $0.4\sigma_r$ is the design strength on the timber-bearing surface considering the creep phenomena and σ_f is the applied stress due to the maximum force developed in the post-tensioning bars. The shear and moment strength of the panel reduced section must be checked to resist the envelopes of the NLTHA results. Also, to allow the maximum resistance to the shear through thickness induced by the post-tensioning bars, the opening in the panel is positioned in the middle of the height of the panel to maximize the length of the shear planes.

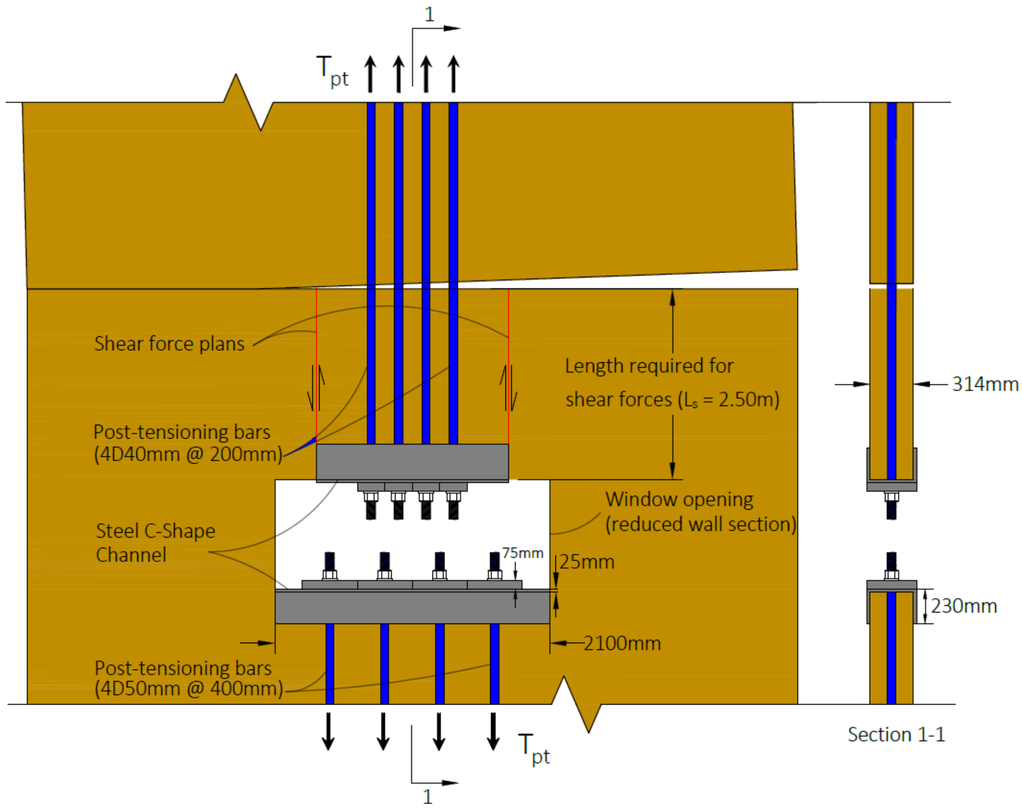

FIGURE 3.10 – Connection design for multiple rocking segment system of wall M1X

3.5 Conclusion

The current study is focused on the analysis of a CLT multiple rocking segment system to resist the seismic forces. First, a comparison of the NLTHA results for the single and multiple rocking segment systems developed in a previous research is shown. Second, an 11-storey case study building in Vancouver, Canada, is designed using the DBD procedure. The NLTHA of the lateral-force-resisting system is performed to determine the inelastic seismic demands and displacements of the building. The results of this research demonstrate relevant ideas for further development and implementation of the low-damage seismic design methodology and consideration of higher mode effects in the building codes. Base on the analyses, the following conclusions have been made :

— NLTHA results comparing CLT single and multiple rocking segment systems showed that the shear and bending moment envelopes can be significantly reduced by allowing a gap opening between the wall segments along the height of the building. Due to the lower forces, it is possible to design a system with reduced walls cross sections, post-tensioning bar areas and lower initial pre-stressing, resulting in material and labour costs savings.

— The design considerations and NLTHA results on the numerical models of an 11-storey building showed that the CLT multiple rocking segment system is viable for this type of structure and location. The connection detailing between the panel segments requires only a C-channel beam and a few plates and nuts, thus resulting in a more economical solution than the rigid connection of the single rocking segment system which requires thousands of fasteners.

3.6 Acknowledgments

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Conclusion

Ce projet de recherche est porté sur le développement d'un SRFS Pres-Lam pour les bâtiments multi-étagés de 3 à 11 étages. Une revue de littérature sur le sujet est présentée dans le chapitre 1. Dans le chapitre 2, les analyses sont faites en comparant les systèmes à section basculante simple et multiples en CLT et en LVL. Des études analytiques sont tout d'abord effectuées pour comparer les exigences de conception des murs en CLT et en LVL. Ensuite, des analyses temporelles non linéaires sont menées sur des modèles numériques représentant les configurations des murs et des bâtiments d'études pour évaluer l'effet de l'amplification dynamique des efforts sismiques. Dans l'objectif d'atténuer cet effet, des études sont effectuées sur des systèmes à sections basculantes multiples en permettant le basculement des sections aux joints de construction avec l'utilisation de connexions simples. Dans le chapitre 3, une analyse et conception complète d'un bâtiment de 11 étages sont produites en utilisant des SRFS Pres-Lam en CLT à sections basculantes multiples. Les conclusions et recommandations tirées de cette recherche sont présentées aux points suivants :

- Objectif 1 : Pour obtenir le même comportement d'un mur en LVL, le mur en CLT doit posséder des dimensions 20% supérieures dues à des résistances mécaniques plus faibles et la présence des couches perpendiculaires à la l'application de la charge. Les dimensions des murs en CLT restent tout de même raisonnables. Donc, dans un contexte où le projet est situé dans un endroit où le CLT est très présent sur le marché, l'utilisation du CLT dans les systèmes Pres-Lam peut être une option envisageable.
- Objectif 2 : Un SRFS Pres-Lam en CLT et en LVL à section basculante simple sera sujet à des amplifications dynamiques des forces sismiques aux étages supérieurs dus à une flexibilité importante du bois. Ce phénomène fait augmenter les charges de conception et donc ainsi les sections des éléments du système. Pour des bâtiments de trois étages, ces effets n'ont pas beaucoup d'importance, pouvant être même ignorés. Pour des bâtiments plus hauts, l'amplification dynamique crée des efforts non négligeables à considérer lors de la conception.
- Objectifs 3 et 4 : L'utilisation des connexions simplifiées permettant le basculement des sections aux joints de construction des étages supérieurs réduit significativement l'effet des amplifications dynamiques. Des réductions de 40% des efforts de conception peuvent

être obtenues réduisant au besoin les sections des éléments des SRFS. Pour les bâtiments de 9 à 11 étages, même si une grande réduction des efforts est notée, de l'amplification est toujours présente aux derniers étages du bâtiment. Les connexions développées pour les murs à sections basculantes multiples nécessitent moins de temps de main d'oeuvre et de matériaux que les connexions typiques utilisées pour les murs à section basculante simple.

— Objectif 5 : La procédure de conception d'un système Pres-Lam en CLT comme SRFS de bâtiments multi-étagés au Canada est développée dans le chapitre 3. Les recommandations suivantes sont proposées. Premièrement, l'utilisation d'une conception par déplacements (DBD) est très pertinente pour effectuer l'analyse sismique de ce type de SRFS n'ayant simplement qu'à imposer à la base des murs la rotation coïncidant avec le déplacement de conception prescrit par les codes. Deuxièmement, vérifier que la résistance en compression axiale des panneaux de CLT est suffisante sur la portion résiduelle en contact avec le sol lors du basculement des sections pour qu'il ne se produise pas de déformations plastiques dans le bois. En effet, due à la combinaison des charges axiales et de moment de flexion, cette vérification de résistance gouverne la conception des sections des murs. La résistance d'un panneau est affectée par le fait que seulement les couches parallèles à l'application de la force sont considérées dans les analyses. Troisièmement, porter une attention particulière à la connexion entre les panneaux des murs à sections basculantes multiples pour qu'il ne se produise pas d'écrasement du bois, pour que l'attache en "C" en acier ne se déforme pas de façon plastique et pour que les résistances résiduelles suite à l'ouverture du panneau soient toujours supérieures aux efforts sismiques. Quatrièmement, vérifier que l'enveloppe des résistances de la base jusqu'au sommet des structures est supérieure aux forces sismiques amplifiées dues à la flexibilité des structures en bois. Le cheminement détaillé est présenté dans l'Annexe B.

Les études effectuées dans le cadre de ce projet de recherches étaient analytiques et numériques. Pour valider les hypothèses quant aux résistances des éléments et les différentes interactions entre eux, des essais expérimentaux pourraient être effectués dans le cadre d'un autre projet futur pour développer davantage les SRFS Pres-Lam en CLT. En effet, des tests pourraient être effectués sur les détails de la connexion développée, sur la rigidité des connexions dans le CLT et dans le LVL, sur les résistances aux déformations plastiques et sur la résistance en compression et en cisaillement dans le panneau.