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Active Damping for Cross-Laminated Timber Structures to Improve Seismic Performance

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ABSTRACT: During seismic events, multi-story cross laminated timber (CLT) buildings may be able to achieve damage-free performance through adequate connection between CLT wall and floor diaphragm panels. However, amplification of seismic accelerations associated with these rigid connections may result in occupants' injury and contents damage, thus being unacceptable from a serviceability standpoint. This study looked into the feasibility of incorporating hysteretic damping and ductile response in only selected stories of a multi-story CLT building for better seismic performance. CLT wall system is a suitable candidate to implement this idea due to its ability to achieve both rigid and ductile lateral resistance responses by simply changing the detailing. Acceleration and displacement levels under maximum credible earthquake (MCE) level seismic hazard from variations of an example 10-story building are compared. One building designed utilizing a strength-based approach utilizing rigid CLT wall detailing, and other buildings was modified from the rigidly designed building by introducing ductile stories with different properties. The numerical results showed that seismic performance, particularly story acceleration and inter-story displacements, can be reduced dramatically for most stories by incorporating ductile layers in a rigidly connected CLT building. The damage free performance for multi-story CLT building in a MCE level event is possible through the inclusion of hysteretic damping at only selected locations.

KEYWORDS: Cross-Laminated Timber, Mid-Rise Buildings, hysteretic damping, seismic response, acceleration.

1 INTRODUCTION

A large percentage of the U.S. population lives in areas classified as urban or suburban and this number continues will continue to rise with each census. This situation necessitates unban infill structures that can provide relatively dense habitat. Ten- to twenty-story tall buildings are ideal for this application because they can provide the owner with the flexibility to strike an optimal balance between land price and the cost of design and construction. It is not feasible to construct traditional light-frame wood buildings at these heights due to fire consideration. But a relatively new wood based system, namely cross laminated timber (CLT) construction, can be a viable candidate for multi-story wood buildings over 10 stories. With heavy timber fire rating [1], multi-story CLT buildings have been built around the world but mostly in non-seismic regions. Figure 1 showed the concept of CLT panel and a nine-story CLT building constructed in London.

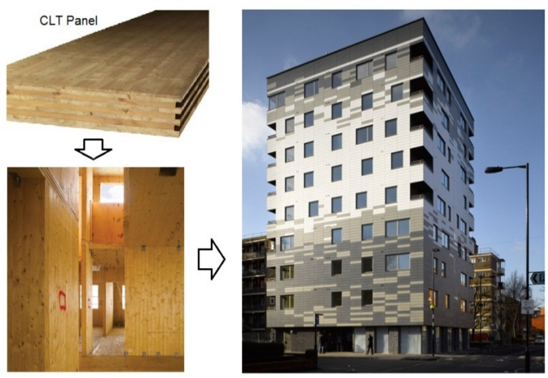

Figure 1: *CLT construction and 9-story CLT building in London*

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In seismically active regions, the needs for buildings to remain usable immediately following design or even higher level earthquakes is the key for achieving a resilient society at large. However, multi-story buildings that are between 100 to 200 feet in height typically have relatively short natural period and rest in the peak region of design response spectra curve, which indicates the seismic demand on these structures can be quite significant. In addition, the amplification of ground acceleration in these buildings can be very large so that excessive damage to building contents may occur during large earthquakes [2], even when the structural strength is adequate. Acceleration for multi-story buildings has not been a focus for seismic design from the very beginning. Traditional force-based design procedures focus on providing adequate strength for the structural elements in order to prevent collapse. The recent development of performance based seismic design (PBSD) [3] has extended this consideration to other performance measures from a system perspective. Most of existing PBSD procedures, however, focuses mostly on building displacement or deformation [4], which does not necessarily lead to satisfactory performance in limiting seismically induced acceleration. A handful of researchers also looked into derived performance objectives such as economic loss, e.g. the ABV proposed by Porter [5], and applied by Pei and van de Lindt [6] in loss-based seismic design. These studies consider acceleration as one of the performance metrics, but were typically done for low-rise light-frame wood buildings. Recently, Liu and van de Lindt [7] developed simplified PBSD procedure to predefined acceleration performance target using shear wall selection tables.

Traditional strength based seismic design of multi-story structures utilizes equivalent lateral force distribution over building height to ensure seismic demands at each story is exceeded. This design approach typically results in a gradually increasing strength profile from top of the building to the bottom. The ductility demand of the structure is also implicitly satisfied by ductility of each story. In this study, a different approach is taken to concentrate ductility demands for the entire structure at several selected stories, while keeping rigidly connected CLT walls in other stories to simplify construction and save costs. This concept is similar to an inter-story isolation configuration [8]. But will be more feasible to implement as the detailing to introduce ductility and hysteretic damping in CLT construction is very straight forward. It is anticipated that the acceleration experienced within the building will also be smaller than that from a traditional rigid construction.

As the building designed to concentrate seismic deformation and damping in selected stories, these stories must be able to resist P-Δ induced collapse under relatively high drift levels. Another advantage of using CLT is its robustness against "pancake collapse", which is a problem for light-frame wood construction under large drift levels. The CLT panelized construction is a cost-effective, time-saving, and environmental friendly solution for urban infill and has been successfully used to construct tall buildings in low seismic regions. The CLT floor diaphragms are constructed from solid CLT panels which have nearly rigid in-plane behaviour, which is plausible for numerical modelling and added to the credibility of the numerical simulation results presented here.

2 CONCEPT

The behaviour of the proposed multi-story system can be idealized as relatively rigid "story blocks" separated by ductile deformable layers that are capable of developing hysteretic responses. As it is shown in Figure 2, instead of using lateral force resistant system with gradually increased strength and stiffness along different stories of the CLT building (traditional system), two types of story configurations will be used, namely rigid elastic stories which will be designed to behave approximately in the linear and damage free range, and the ductile stories that incorporates large deformation capacity with hysteretic damping. By adjusting the location and ductility characteristics of the ductile stories, the overall seismic response of the structure can be improved. The ductile stories will engage similar to isolation layers, which will in turn reduce the force demand on rigid stories. However, the ductile stories will be much stronger than isolation layers and be more economical to build.

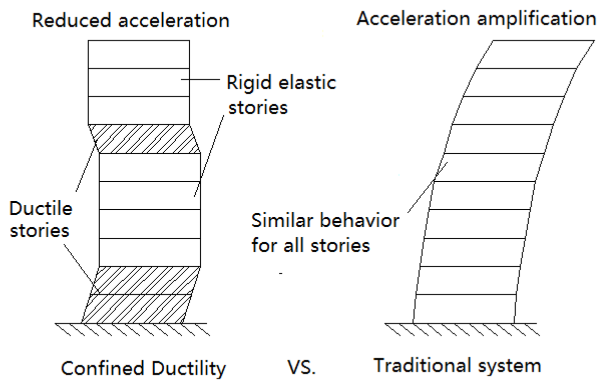

***Figure 2:** Distributed ductility and damping concept for multi-story buildings*

Two types of wall configuration will be employed to realize the ductile and rigid story behaviour. Since the CLT walls can be manufactured as very long wall panels (typically has doors and windows pre-cut in them if needed), fixing a long CLT panel with adequate wall to floor connectors will create a shear wall line with enormous rigidity. When the wall is confined by the story diaphragms, the only possible failure mode for this installation detailing will be simultaneous shear failure of all connections at the bottom or top of the wall. If the lateral force at the story does not reach this level, the entire story will act like a rigid box. Figure 3 showed this rigid CLT wall detailing conceptually. The second wall detailing type will be CLT wall made from smaller "rocking" panels with relatively high height to length ratio. This configuration will allow individual panels to rotate (i.e. rock) and develop relatively ductile lateral responses. In addition, pre-defined gaps can be left between these short panels to further increase ductility of the assembly, as the panels will be free to rotate to a certain level before bearing on each other. The concept of this ductile wall detailing is also shown in Figure 3.

Note that for all walls in the rigid story discussed above, rigid wall detailing should be used if it is architecturally possible. And the length of the wall panels should be maximized to increase the integrity of the rigid story. For walls in a ductile story, longer ones should be broken up into short panels. Thus all walls in a ductile story should be multi-panelled walls once the length exceeds a certain amount. In this study, 1.22m x 2.44m (4x8ft) size was adopted as the standard dimension for short rocking panels. As it is shown in Figure 3, the strength and stiffness of both wall configurations should be adjusted through the arrangement of connector brackets between wall and diaphragms. Typical CLT construction details may be somewhat different from it is shown in Figure 3, e.g. no brackets on the top of the wall. But keep in mind that this study is to investigate the feasibility of the concept numerically, thus Figure 3 only represents one possible configuration to realize the needed response characteristics for CLT walls.

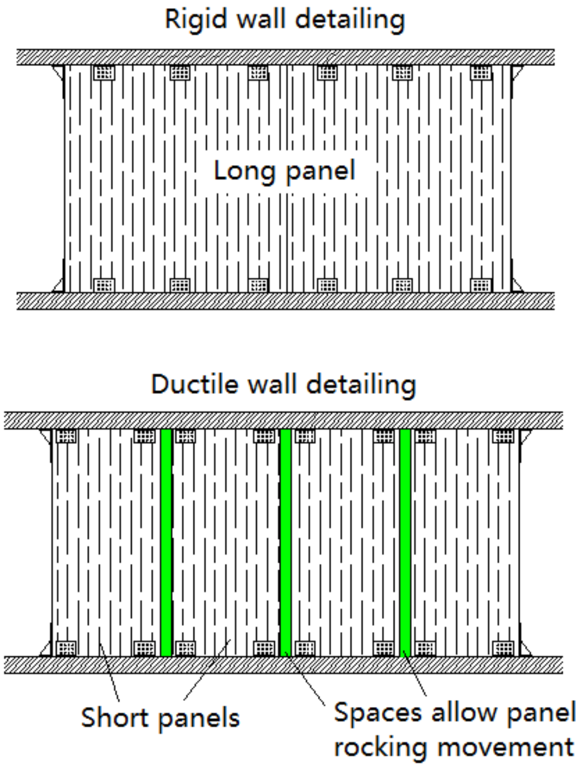

Figure 3: *Two types of CLT wall detailing method*

3 NUMERICAL MODELLING

In order to verify the aforementioned concept, numerical models for the proposed CLT wall and system need to be developed. While there have only been very limited CLT system (building) level tests [9], a good number of studies on CLT wall behaviour has been conducted around the world in the past decades [10][2]. Results from quasi-static tests on CLT wall panels showed that the connection layout and design has a strong influence on the overall behaviour of the wall and the resulted system can be very stiff [11]. The ductility of the system is associated with the slip and deformation at the panel-floor interface connection. Quasi-static monotonic and cyclic tests have been carried out on CLT walls to study the influence of boundary conditions, magnitudes of vertical load and the type of anchoring systems [12]. A recent study conducted by FPInnovation [2] tested multiple CLT walls under monotonic and cyclic loading protocol to study the impact of connector type and arrangement to CLT wall resistances. Among the walls tested, there are a few cases that are similar to the ductile wall detailing configuration discussed here, e.g. Figure 4.

Figure 4: *Example for multi-panel CLT wall test set-up (Popovski 2010)*

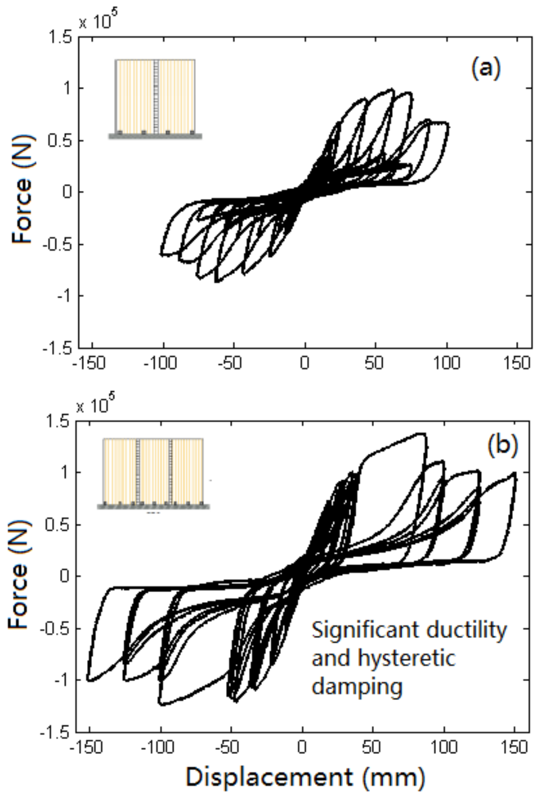

Figure 5: *Ductile response of multi-panel walls under cyclic tests*

The test results showed that long CLT walls consist of multiple short panels can achieve satisfactory ductility and hysteretic energy dissipation. As one can see from

Figure 5, hysteretic responses from both the 2- and 3-panel walls exhibited significant level of ductility and hysteretic damping.

In this study, the behaviour of multi-panel walls are simulated using a simplified numerical model developed in a relevant study by Pei et al. [13] based on the test data from [2]. A ten-parameter hysteretic model (see Figure 6) widely used in wood connection modelling [14] was used to characterize the connector and wall behavior. With the hysteretic parameters of the model calibrated based on test results in [13].

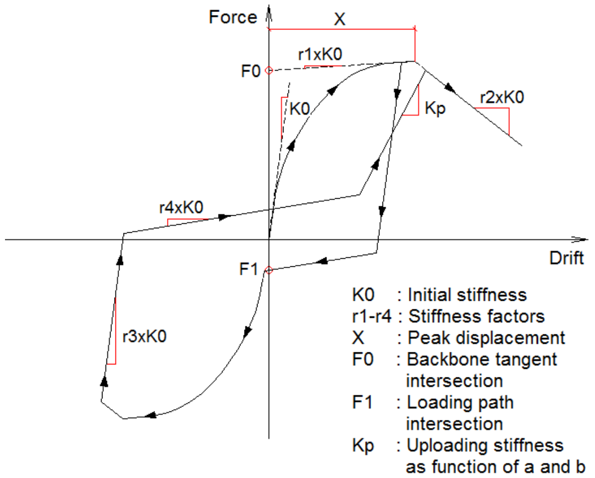

***Figure 6:** Ten-parameter hysteretic model for CLT wall modelling*

Experimental results for rigid wall detailing, i.e. extremely long CLT walls rigidly connected to the floor, was not available to the authors for this study. However, it is reasonable to assume a simple failure mode for this type of wall, which is the sliding of the entire wall relative to the diaphragm, thus failing all connectors. Based on this assumption, the lateral response of the wall will simply be the sum of all failed connector responses. The connector slip relationship and parameters obtained from Pei et al will be used for the numerical modelling in this study, which is a 16d spiral nail connected through a Simpson Strong-Tie 90mm x 105mm x 105mm connector bracket. It is assumed that the same type of bracket and nails will be used for the entire building in this study. The parameter for the nail was listed in Table 1 for a single nail connection. A bracket will typically take 6 nails. Thus a rigidly connected long wall segment with 10 bracket connection will have 60 times the capacity of a single nail connector, while the ductility will remain the same, as all nails will deform the same amount as the wall will upon failure. Note a long wall segment with window openings, such as the one shown in Figure 7, will be treated as a solid wall for this purpose, because the existence of window does not affect the failure behaviour and strength of the rigid walls.

***Table 1:** Calibrated CLT connector parameters*

Connector Type	Hysteretic Parameters (N, mm)				
	K0	r1	r2	r3	r4
16D-SN	140	0.005	-0.2	1	0.01
	F0	F1	X	a	b
16D-SN	3558	178	64	0.5	1.1

***Figure 7:** Single panel configuration for rigid wall detailing*

Based on the nail connector parameters and numerical model for CLT walls, the cyclic response and backbone for two 6.1m (20ft) CLT wall segment constructed using ductile and rigid detailing were presented in Figure 8. It can be seen from the comparison that the response of CLT wall is highly adjustable. The rigid detailing wall has very high stiffness and an approximate linear response range compared to the ductile wall. While significant level of ductility and energy dissipation was achieved by the ductile detailing. The ductile results shown were achieved by breaking up the wall into 1.22m (4 ft) panels and only attaching brackets at the corners of each panel. The rigid wall has a solid 6.1m (20 ft long) panel. Based on calculation, the approximate linear response capacity (i.e. the load at which the response divert from linear) for a single bracket with 6 spiral nails is close to 12.5kN. This value will be used to select the number of bracket later when design for rigid floors.

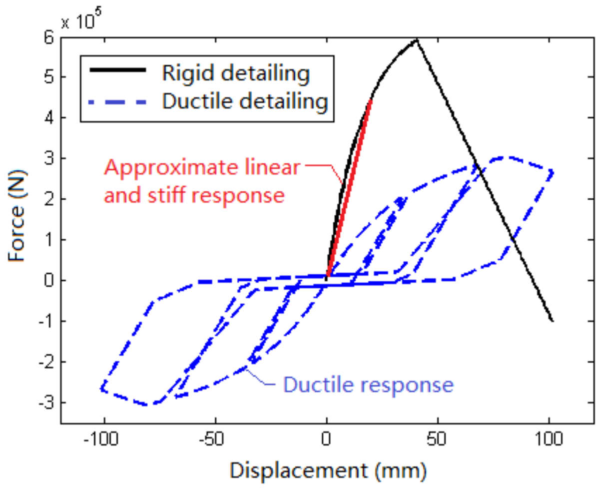

***Figure 8:** Ductile and rigid responses comparison for from two 6m wall segments*

At the system level, a shear bending coupled model was used to simulate the structure response under seismic excitation. The analysis was conducted using a software program: Seismic Analysis Package for Woodframe Structures (SAPWood) [15], which is a numerical tool specially developed to conduct nonlinear time history analysis for light-frame wood buildings. But the program is general enough to incorporate other hysteresis models such as the model for CLT walls presented here. The program is part of the NEESWood project and has been validated by numerous component and system level shaking table tests, including the 6-story NEESWood Capstone building. It is also proven to be suitable to model system with overturning behaviour coupled together with lateral displacements [16]. Simple schematic of the model was shown in Figure 9. One can see each floor diaphragm was assumed to be rigid plate with 6 DOFs, which represents CLT floor diaphragm pretty well. The diaphragms are connected by a generalized hysteretic spring elements at designated locations. The seismic mass is lumped at the diaphragm level.

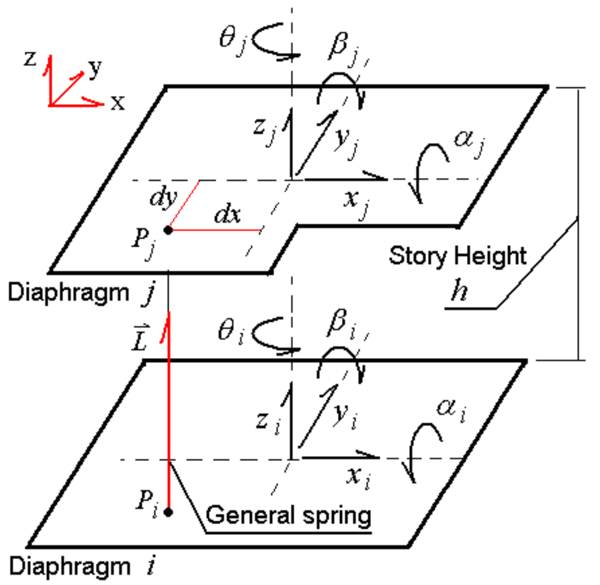

Figure 9: System level numerical model for time history simulation

With these numerical tools in place, once the configuration of the walls in each story is determined, a numerical model of the structure can be established and nonlinear time history analysis can be conducted to estimate the structure responses during earthquakes.

4 PERFORMANCE EXPECTATIONS

Recall that the objective for introducing this new system is to reduce high acceleration levels in multi-story CLT buildings. The floor acceleration is without doubt a focus for this study. However, it is also expected that the displacement for the rigid stories should not exceed the approximate linear limit for the walls, or in another words, the force demand in these stories does not exceed the story capacity. Also the displacement in ductile stories should not exceed the displacement capacity of the multi-panel walls. The acceleration of concern in this study is the absolute acceleration experienced at each floor relative to fixed coordinate, rather than acceleration relative to the moving ground. Thus the performance metrics that will be considered in this study include inter-story drift of each story and peak absolute acceleration at each floor level, for both rigid and ductile structures.

Typically for PBSD, a design performance target will be pre-defined and designed for. However, because the currently study looks only at the feasibility of utilizing the distributed ductility and damping system, design procedure to achieve a predefined performance target will not be developed here. However, this is a worthy effort to undertake as the next step of this study to enable systematic design of such structures. The objective of this study is to verify numerically that significant improvement on the seismic performance metrics can be achieved using the new system when compared with the traditional rigid system.

5 PROTOTYPE BUILDING

As a first cut for this study, a ten-story residential building was developed as the prototype structure using the floor plan of the NEESWood Capstone structure (a six-story light-frame wood apartment building tested at Japan's E-Defense shake table in 2009 [17]). The elevation and floor plan are presented in Figure 10. The building foot print is about 12 x 18 meters, with total height of 27.4 meter. All floor plans are assumed to be identical with 4 living units. The seismic weight of the building was assumed to be 2.2kN/m^2 for the first story, 1.4kN/m^2 for the roof, and 2.1kN/m^2 for all other stories. The total building weight is 4,537kN (462 metric tons). Neglecting some interior wall lines, the building provided about 55m (180ft) of CLT wall lines in each direction for the designer to utilize. The exterior walls are shown with window openings removed from the wall line. However, for CLT panels the windows are typically pre-cut into the wall panel, so the window opening will not significantly affect the strength of the outside wall segments. For the interior, the door openings do interrupt the CLT walls (due to the height of the door openings) so these walls are broken into smaller segments. The interior walls that are neglected in structural design can just be installed with minimal connection. Another concern for realistic design will be inclusion of anchoring tie-down system through different floors to ensure vertical load path against overturning. This detail is not considered in this study (assuming there will be adequate over-turning connection) but should be handled with extra care in a realistic design.

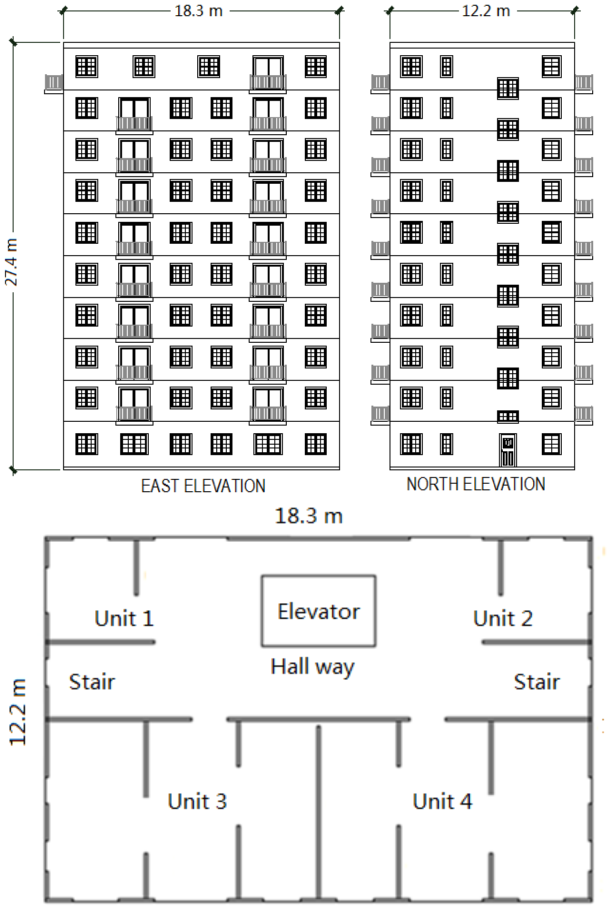

Figure 10: *Example building elevation and floor plan*

Force-based design based on ASCE7

Equivalent lateral force procedure based on ASCE7 [18] was conducted for rigid building design in order to identify the needed story shear demand. The seismic hazard was taken from seismic hazard map for Los Angeles CA. A previous study by Pei et al concluded that a R factor of 4.3 could be used for this type of system if one needs to control damage to the building. But that study is based on using all ductile construction and considering a nominal CLT wall capacity approximately equals to 40% of the ultimate strength. For this study, it is decided to use a R factor of 2.0 for the rigid construction, while selecting wall configuration based on the linear strength limit calculated earlier (approximately 12.5 kN/bracket). Note that the intention of this design is to achieve damage free performance using rigid construction. Although the selection of R factor is quite arbitrary, the results obtained from the comparison between two design styles should still be valid. The design story shear for the ELF force demand for the building was listed in Table 2 together with the hazard parameters used to develop the design. One can see that the walls were selected so that the "as-design" capacity was always greater than the demand calculated from ELF. The "as-design" capacity was calculated based on the rigid wall linear limit. The number of brackets needed per linear meter of the wall is also given in the table for the corresponding stories.

Table 2: *ELFP design of the 10-story rigid CLT building*

Cs	I	Tn	S_{DL}	S_{DS}	R	
0.23	1	0.58	0.57	1.62	2	
Story	H (m)	Wi (kN)	Fi (kN)	Vi (kN)	As-design (kN)	#B/m*
1	2.7	489	40	2209	2250	3.3
2	5.5	467	80	2168	2250	3.3
3	8.2	467	123	2088	2250	3.3
4	11	467	167	1965	2250	3.3
5	13.7	467	211	1799	1800	2.6
6	16.5	467	256	1588	1800	2.6
7	19.2	467	301	1332	1500	2.2
8	21.9	467	346	1031	1125	1.6
9	24.7	467	392	685	750	1.1
10	27.4	311	292	292	562.5	0.8

* The number of brackets to be installed at wall-diaphragm interface per-meter for the rigid wall panel detailing

Incorporating ductility

Ductility and hysteretic damping can be introduced by simply breaking up solid long wall panels to short panels and installing brackets at the corners of these sub-panels. The strength of the ductile stories can be further adjusted by changing the number of nails on each bracket, intentionally leaving out wall segments, etc. There are several variables in the design process; firstly the number and location of the ductile stories, and also the strength (correlated to the stiffness) of the ductile story. In this study, three ductile stories were inserted into the 10-story building at Story Levels 2, 5, and 8. Then three different configurations, namely Ductile, Ductile_A, and Ductile_B, were conducted to study the impact of the stiffness and strength of these stories to the overall building displacement and acceleration performance. The strength of Stories 2, 5, and 8 of the Ductile configuration were taken as approximately 1/3 of the original rigid story capacity. The Ductile_A configuration increases the strength of these stories by 50% while Ductile_B configuration corresponds to 50% decrease. Figure 11 showed the backbone curve of Story 2 in three variations compared to rigid design. After introducing these ductile stories, the stiffness profile of the building becomes "irregular" as there is significant difference in stiffness and strength properties between adjacent stories. However, the effect of this irregularity is adequately considered here with nonlinear time history analysis.

For all three ductile configurations listed, corresponding CLT wall connection details were determined and listed in Table 3. The minimal rocking panel numbers should be included in both the long and short direction. Table 3 also listed the initial natural period of the building with the ductile layers inserted. As one would expect, the introduction of these weakened layers elongated the building natural period from the period of the original design 0.73 second. Keep in mind that the natural periods listed here were calculated based on the initial tangent stiffness. The building natural periods with ductile layers will further elongate as these layers deform into nonlinear range.

Table 3: *Ductile configurations for the example CLT building*

Story	Minimal # of rocking panels*			Tn (sec)
	2nd	5th	8th	
Ductile	16	14	7	1.18
Ductile_A	24	21	11	1.02
Ductile_B	8	7	4	1.57

* Rocking panel is a 1.22m x2.44m (4x8ft) CLT panel connected to floor and roof diaphragm with 4 brackets.

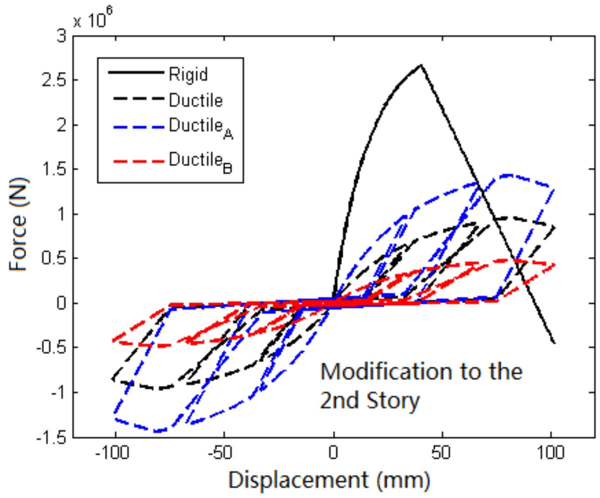

Figure 11: *Story backbone curve for rigid and ductile designs*

6 System performance

The models for the as-designed CLT buildings were constructed in SAPWood and subjected to a suite of earthquake ground motion records scaled to the MCE hazard level corresponds to Los Angeles CA. The ground motion suite recommended for use in the U.S. Federal Emergency Management Agency Document P-695 [19] was adopted in this study, which includes 22 bi-axial far-field ground motions. The response spectra of all these ground motions scaled to the Maximum Credible Earthquake (MCE, level 3) hazard level is shown in Figure 12.

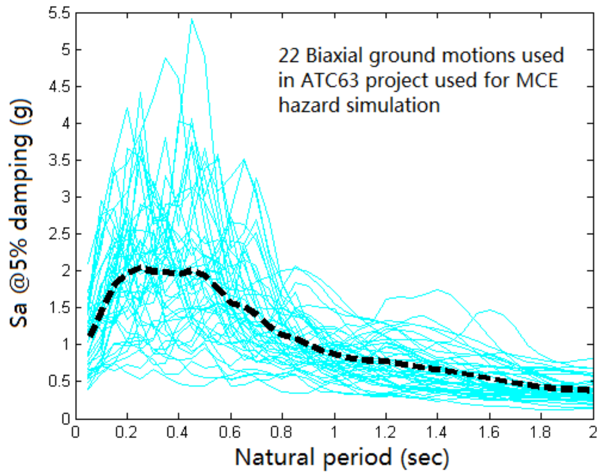

Figure 12: *Response spectra for MCE level ground motions from ATC63*

The average (from all 22 simulations) relative maximum displacement profile of all stories over height is illustrated in Figure 13 on the left. It can be seen that the configuration with ductile stories did produce larger overall displacement. However, the deformation was mostly concentrated in the ductile stories; and every ductile story attracts a fair amount of deformation. Figure 13 also showed on the right the profile for the average maximum inter-story drift within the building. The ductile stories have similar behavior in that they absorbed significant amount of inter-story drift. The direct benefit is the dramatic decrease in deformation for other stories (approximately 50% decrease can be observed for most stories compared to the rigid design). As the non-ductile story mostly performed linearly, this decrease indicates decrease in seismic force demand in those stories as well. More important, all ductile stories have less than 3% inter-story drift (about 80mm displacement) on average, which is well within the ascending portion of their hysteretic envelope. This indicates there is still strength reserved in these stories for the MCE events.

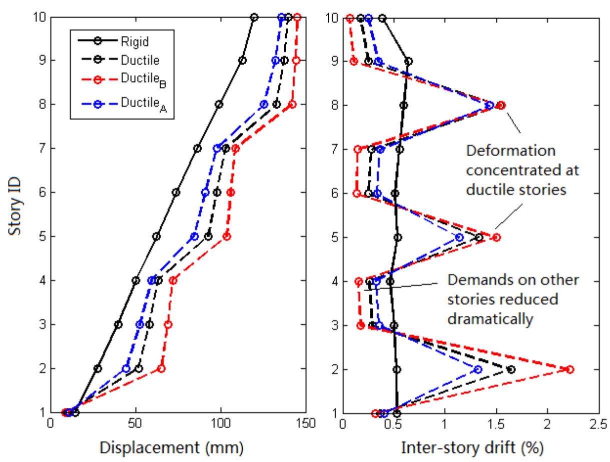

Figure 13: *Average maximum inter-story drift profile comparison.*

The average maximum acceleration experienced on each floor was shown in Figure 14. It can be seen that the linear rigid building has some higher acceleration levels over 2g. Adding ductile stories was shown to be very effective in reducing floor acceleration. For the configuration with the most ductile stories (Ductile$_B$), average maximum acceleration for all floors (except for the first floor) was reduced by more than 50%.

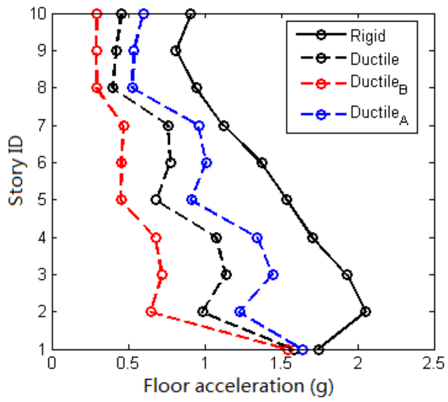

***Figure 14:** Average maximum story acceleration profile comparison.*

Figure 15 showed the empirical distribution of maximum floor acceleration from all time history simulations for selected stories. The advantage of incorporating ductile stories in multi-story CLT building for acceleration control is quite evident.

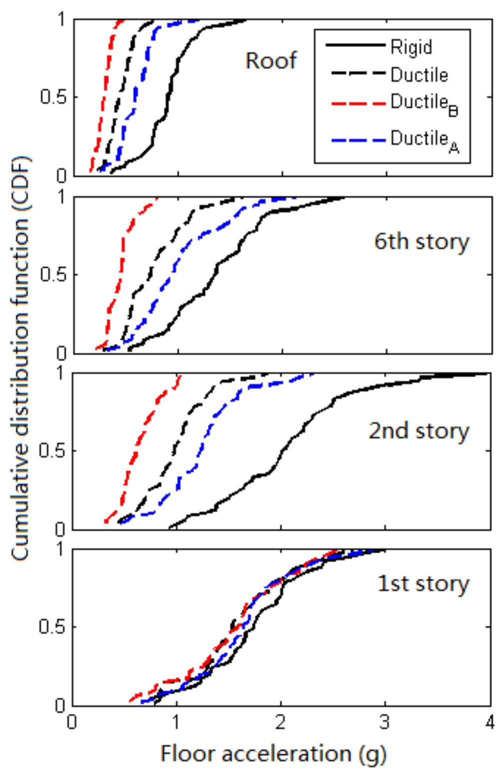

***Figure 15:** Distribution of maximum story acceleration for selected stories.*

7 CONCLUSIONS AND RECOMMENDATIONS

The studied presented in this paper provides insight into the feasibility of an innovative idea to economically build multi-story CLT buildings in high-seismicity regions and provides highly resilient behaviour. The concept of altering selected stories to enable ductile behaviour allows the mitigation of acceleration experienced by the occupants during an earthquake event. The majority of the stories can be constructed rigidly to maximize the efficiency for the pre-fabricated CLT construction. With the reduced force demands resulted from ductile response of selected stories, these rigid stories can remain damage-free during a major event. The numerical simulation conducted in this study illustrated that the overall concept of distributed ductility and damping is feasible and very effective, but the procedure that can be used to systematically design and optimize this type of system still needs to be developed.

Results from this study were limited by the fact that the numerical model used in this study was based on limited experimental data, and the test data for rigidly connected wall panels under realistic as-build boundary condition is not available. However, the study does open the door for developing performance based seismic design procedures for CLT buildings with the proposed configuration, which should be a future research direction that is worth pursuing.

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