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Shaping Cross-Laminated Timber Panels to Rock and Roll as Seismic Pendulum Isolators

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ABSTRACT: While research of Cross-Laminated Timber (CLT) structures prioritizes force-based design for earthquake hazards, this project navigates a complementary displacement-based route—charted by United States building code provisions for seismic isolation. Curvilinear cuts to the load-bearing edges of stock CLT panels enable walls to roll through pendulum motion. Elliptical geometry provides the mechanism to lift supported storeys, passively self-centre through oscillatory damping, and avert damage to the panel corners. Wider elliptical profiles reliably negate residual displacements, as a consequence of greater eccentricity between the contact forces. Panels shaped to lesser elliptical eccentricities, however, isolate superstructures more effectively by lengthening the rocking period as much as 1.5 seconds and adding greater than a metre of lateral displacement capacity. Physical models at 1/12th scale, computer simulations, and tests of the contact behaviour between CLT panel edges and boundary materials, answer practical questions about how connections and friction profoundly alter the rocking kinematics. Full-scale prototypes of 5-Layer CLT panels—respectively measuring 2.44 by 3.66 by 0.17 metres in width, height, and thickness—compare 3 rocking versions of rolling isolation. This paper presents the strategy and initial data qualifying CLT for versatile use as soft-storey isolation within multi-storey schemes—to achieve earthquake-resilient performance.

KEYWORDS: Cross-laminated timber, rocking wall systems, rolling seismic isolation, earthquake resiliency

1 INTRODUCTION

Many wood industry hubs around the world coincide with regions of high seismicity. Japan, New Zealand, and Chile represent a few of the many countries seeking multifaceted solutions for cross-laminated timber (CLT). This paper focuses on the West Coast of the United States, and Pacific Northwest region in particular, to demonstrate that CLT panels can cost-effectively accomplish seismic isolation, in order to fulfil economic and environmental benefits of mass timber construction in the face of formidable earthquake hazards.

1.1 REGIONAL ECONOMICS

The west coast of the United States supports a sizable forest products industry, with many economic incentives to encourage panelised cross-laminated timber (CLT) construction. Keegan et al. quantified steep declines in sales, employment, wages, production capacity, and utilization ratios of wood products, throughout the Western U.S. forest products industry, during a period of recession following the 2006 economic peak [1]. The staggering impacts of multi-billion-dollar losses and thousands of job cuts that Keegan et al. attributed to a historical plunge in the housing market, highlight the fragility of a timber industry that relies too heavily on low-rise residential construction. Cross-laminating technology can grow the forest products industry, beyond residential market constraints, by assembling and adhering high volumes of lumber into composite panels of sufficient size and strength to usher prospects of wood structures in commercial sectors. With ability to rise many storeys taller than conventional wood construction, CLT, therefore, offers the Western forest products industry broader economic resiliency.

Green building markets of the West Coast can further cultivate the growth of CLT structures. Outlining sustainable research initiatives for U.S. forest products, Ritter et al. cited a growing body of science touting the eco benefits of wood construction and identified CLT for its potential to offset forest management costs with increased demand for small-diameter trees [2]. Proponents of tall wood buildings, such as Skidmore, Owings, and Merrill, LLP, have hypothetically illustrated drastic reductions in carbon emissions, in terms of *embodied energy*, that CLT panels can achieve when substituted for concrete slabs in high-rise structural schemes [3]. Knowles et al. found many leading commercial building design professionals in the state of Oregon eager to envisage mass timber construction on virtues of sustainability, but many designers indicated that building codes most often steered structural selection toward more established systems [4].

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Pending building code revisions, based on the proven ability of CLT to rise safely and substantially taller than conventionally framed timber, will likely open markets in the West Coast—to an extent. The International Code Council (ICC) Ad Hoc Committee on Tall Wood Buildings, for instance, has proposed changes to the 2018 edition of the *International Building Code* that would permit CLT structures to rise as tall as 12 storeys. [5]. In a region subject costly earthquake damage, however, building code acceptance represents only an initial step toward industry implementation of CLT. The Federal Emergency Management Agency (FEMA) estimates that West Coast states collectively incur over 4.5 billion dollars of "Annualized Earthquake Losses" [6]. The calculated earthquake damages have occurred despite general adherence to seismic building code standards, which suggests room for improvement. Seismic solutions for CLT, therefore, must capitalise on the opportunity to perform better than currently prequalified options, to raise its value.

1.2 SEISMIC QUALIFICATION STRATEGIES

The "Structural Research Drive" mapped by Pei et al. comprehensively strategized the seismic qualification process, using three main performance tiers ranging from minimum life-safety requirements to *resilient* performance [7]. Efforts to proliferate CLT structures across the range of seismic objectives are currently in progress. The following sections relate the performance tiers to specific sections of U.S. building standards for seismic design, for comparison with the seismic isolation performance specifications.

1.2.1 Force-Based Seismic Design

The foundational performance tier that Pei et al. dubbed "code minimum" satisfies the most commonly applied seismic provisions of the building code [7]. CLT presently lacks official listings of the most commonly referenced seismic performance factors that enable engineering practitioners to readily execute designs. Amini et al. outlined rigorous *FEMA P695* qualification procedures to determine these seismic design parameters specifically for CLT systems [8]. Culmination of the effort will list Response Modification Coefficient ($\boldsymbol{R}$), Overstrength Factor (Ω_o), and Deflection Amplification Factor ($\boldsymbol{C_d}$), references to detailing provisions, and height restrictions—for prequalified design of CLT structures, among tabulated options for other *seismic force-resisting systems* [9].

Codifying basic seismic design parameters for CLT lateral systems will enable engineering practitioners to employ familiar procedures, such as Equivalent Lateral Force (ELF), to distribute earthquake forces within a structure. Force-based procedures, however, prioritize inelastic response. Like *crumple zones* in automobile bodies, *plastic hinging* in building frames sacrifices ductile structural components, in order to protect occupants. In either case, residual damage of a moderate to severe collision or earthquake respectively renders the car or building irreparable.

1.2.2 Alternative Means

For CLT seismic force-resisting systems in advance of ubiquitous code prequalification, projects may seek permits via the "Alternative Structural Systems" section of the building code [9, p. 93]. Alternative provisions require authority from local jurisdiction, independent peer review, and substantiating seismic performance data, equivalent to *FEMA P695* procedures [10]. While alternative provisions may apply to any nonstandard structure targeting standard seismic performance, the extra burden of proof often discourages ordinary use. As an exemplary project, the 12-storey Framework has earned permitting in Portland, Oregon, via the support of various government agencies and extensive validation testing [11]. Framework features vertically post-tensioned CLT, capable of rocking during earthquakes and innovative glulam connections, enabling timber framing to accompany the rocking walls in earthquake response. Pei et al. plan to take full-scale validation of the systems developed in Framework even further, with shake-table testing of a 10-storey CLT structure, in order to develop resilient seismic performance standards [12].

1.2.3 The Path of Least Resistance

Engineers of the Brock Commons designed 17 storeys of mass timber superstructure, made of glulam columns and two-way spanning CLT decks, and a lateral support system of reinforced concrete shearwalls for expedient code approval [13]. The strategy of pairing a timber gravity system with a prequalified steel or concrete lateral system allows taller buildings to immediately benefit from the lightweight and sustainable aspects of wood. Timber decks reduce seismic excitation mass, relative to concrete slabs of comparable depth, and many steel or concrete lateral force systems may rise to heights unlimited by seismic code restrictions. The variety of tall wood building strategies has prompted Foster et al. to categorize various structural schemes [14].

1.2.4 Seismic Isolation Performance Standard

Pei et al. suggests that, among many paths leading CLT toward regulatory acceptance in seismic zones, *resilient* solutions offer CLT the most competitive inroads [7]. Table 1 demonstrates that *seismically isolated* structures target *resilient* performance and outperform more conventional *fixed-base* buildings, particularly as earthquakes intensify [15]. Because *seismically isolated* buildings achieve *resilient* performance, by aiming for continued operation after extreme events, this project applies the *ASCE/SEI 7-16* chapter on seismic isolation as a framework for the development of CLT inverted pendulum isolators [16]. This approach leverages established displacement-based design procedures to demonstrate that deformation capacity, rather than ductility, can accomplish less damaging earthquake response. The recently revamped seismic isolation standard specifies performance provisions to encompass a wide range of isolation technologies and encourage innovation and implementation of isolation systems [15]. Presently, the isolation standard provides the clearest path to both *resiliency* and code *qualification* for CLT.

Table 1: Qualitative Performance Expectations for Varying Earthquake Intensities [15]

Performance Protection from:	**Earthquake Ground Motion Intensity** [a] Minor	Moderate	Major
Loss of life or serious injury	F, I	F, I	F, I
Significant structural damage	F, I	F, I	I
Significant nonstructural or content damage	F, I	I	I

[a] F indicates fixed base (left diagram of Figure 1); I indicates isolated (middle or right diagrams of Figure 1).

2 MECHANICS OF ROCKING

Solutions that leverage rigid-body motion, rather than ductility, pair well with the intrinsic rigidity of cross-laminated timber. Pendulum structures and isolators of various forms offer insight. The following sections briefly examine the evolution of rocking wall systems for comparison with pendulum concepts for CLT.

2.1 ROCKING RECTANGULAR BLOCKS

George Housner presented mechanics of a rocking rectangular rigid block to explain why slender structures fared the 1960 Chilean earthquakes better than seemingly more stably proportioned construction [17]. Despite reductions in seismically-induced forces, Housner cautioned, "At present it is not known how to design a rocking structure to have a specified small probability of failure" [17, p. 417]. Decades since, the precast concrete industry availed rocking technology by safeguarding overturning with vertical, unbonded post-tensioning and augmenting hysteretic damping with a variety of innovative connections strategically placed at panel joint interfaces [18-21].

Several timber adaptations of technologies pioneered in precast concrete have recently demonstrated that CLT can mimic the self-centring rocking of resilient systems [22-24]. Dunbar et al. tested a series of vertically post-tensioned CLT rocking wall assemblies, with various connections to floor elements, and included U-shaped Flexural Plates (UFPs) for a high-performance seismic option [23]. Sarti et al. tested vertically post-tensioned laminated veneer lumber walls with ductile steel bars connecting timber to concrete foundation, for hybrid rocking characteristics [22]. Ganey et al. tested vertically post-tensioned CLT wall-to-floor assemblies with UFPs and documented damage, particular to the orthotropic properties of wood, at panel corners that serve as pivot points in the rocking mechanism [24]. Though local and not critical to the global behaviour of the self-centring rocking wall system, concentrated damage to the pivot points of rectangular panels demonstrates a potential vulnerability in the system. Post-tensioning in wood construction, furthermore, is presently much less commonplace than precast concrete construction.

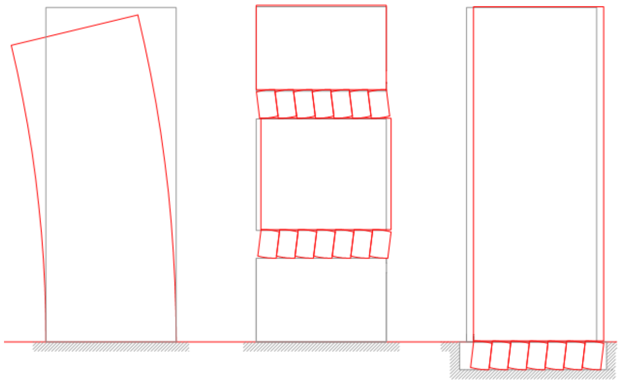

Figure 1: *Fixed base (left), soft-storey isolated (middle), and base-isolated (right) multi-storey schemes.*

2.2 ROLLING ISOLATION

Most rocking chairs are curved to facilitate smooth oscillations, and most rocking chairs are made of wood. Rocking chairs, furthermore, come to rest under the weight of a person, with no post-tensioning required. Rocking with the curvilinear geometry of a common chair requires rolling. Though simple, these concepts are worth investigating in detail, because rolling isolation offers another pathway to resiliency for CLT.

Rolling seismic isolation has a long history, yet lacks the practical development of other pendulum systems [25]. Londhe and Jangid theoretically demonstrated the effectiveness of elliptical rolling rods as base isolation for a relatively rigid superstructure [26]. Londhe and Jangid placed the elliptical rods beneath a relatively rigid multi-storey moment frame with rigid floor masses. The right diagram of Figure 1 illustrates a similar base-isolated configuration with one-storey tall panels. The middle diagram of Figure 1 schematically illustrates a building with multiple soft storeys of isolation. Dolan et al. proposed the concept of numerous isolation planes within a multi-storey arrangement of rigid CLT modules, as a means to more evenly apportion flexibility and control displacement magnitudes [27]. Bolvardi et al. designed a 12-storey CLT building sited in Los Angeles to demonstrate direct displacement design of the inter-story isolation system [28]. This project develops a versatile panel component for both base and inter-storey isolation schemes, based on the geometry of Figure 2.

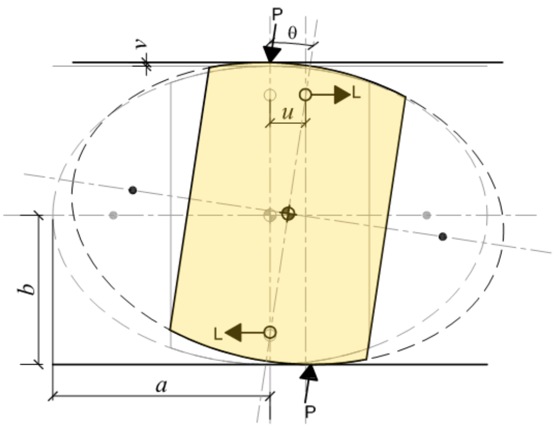

Figure 2: *Rocking CLT panel, shaped from parent ellipse*

2.2.1 Properties of the Ellipse

Figure 2 schematically depicts how a rectangular panel can function as a self-centring isolator, by curving the load-bearing edges to conform to a parent ellipse. To occupy an entire storey, the ellipse height, 2***b*** or twice the semi-minor axis width ***b***, must equal clear-storey height. Varying the ellipse width, 2***a*** or twice the semi-major axis width ***a***, alters the in-plane lateral stiffness, self-centring potential of panels, and reciprocal lateral displacement capacity. Ellipse eccentricity causes panels to incrementally lift superstructures while undergoing lateral displacement. The force couple between contact forces, ***P***, restores the system to its original position as oscillations dampen.

Wider ellipses exhibit high lateral stiffness and restoring moment, but lower displacement capacity and effectiveness as an isolator. Narrower ellipses lessen in-plane lateral stiffness and increase lateral displacement capacity for more effective isolation. Narrow ellipses, however, lessen the moment arm distance between the contact forces that restore panels. If ellipse eccentricity approaches too closely to zero, becoming nearly a circle, panels can settle into a rotated position, instead of returning to the original equilibrium state. Mazzoleni et al. calculated bifurcations for rocking semi-elliptical disks that mathematically explain the instability of ellipse proportions lacking eccentricity [29].

Londhe and Jangid derived equations to facilitate calculations of lateral displacement, ***u***, lifted height, ***v***, and lateral force, ***L***, for a given rotation, θ_r, and given overburden force (vertical component of ***P***) [26]. Notation of Figure 2 differs from the equations of Jangid and Londhe, for design simplification. Figure 2 neglects the weight and inertial effects of the panel, for which Jangid and Londhe provide a detailed accounting. Limits on rotation range must be added, as a consequence of truncating the full ellipse in Figure 2. Constraints that vary from the original concept must also be considered.

2.2.2 Connection Considerations

With adequate traction, the pendulum action of rocking effectively negates residual displacements, but consider that rocking chairs commonly slide on floors after several oscillations. Connections, therefore, must preclude sliding. Loo et al. tested a simple shear pin and bearing plate connection for a rocking rigid-body timber shearwall, in order to transfer lateral forces from the panel to foundation [30]. Pin connections may prove capable of transferring shear effectively enough to prevent sliding, but the path of travel must be predetermined for the pin to accompany rocking with intended consequences.

Displacement restraints for seismically isolated structures help guide components from moving astray. Ideally, however, isolation systems should avoid engaging the limits if possible. Engaging displacement limits too early can lead to premature wear or even alter the rocking motion, so the isolation standard specifies performance provisions regulating *displacement restraints* [16]. Figure 3 illustrates an elevation view of a panel with a curved slot connection that guides pin travel and intends only to resist incidental out-of-plane forces. Tracing the roulette of the parent ellipse determines the slot shape, called an *undulary* [31].

Sacrificial wind restraints keep isolation systems from swaying excessively under wind loading. Standard performance provisions require testing *sacrificial wind restraints* with the complete isolation system [16]. Plates bolted to the outside of the connections shown in Figure 3 lock the main pin in place at low amplitudes of lateral displacement. During the test program, intentionally notched bolts remained intact for low-amplitude cycles and sheared as intended when panels were required to rock beyond wind drift limits.

Connection constraints, in contrast to *displacement restraints*, actively transfer force and consequently alter rocking behaviour. Figure 4 illustrates a steel connection that constrains pin travel horizontally, but permits vertical travel within the slot. The additional horizontal constraint increases lateral stiffness of the system. While the added constraint compromises effectiveness as an isolator, the constraint also increases damping, as the panel must slip along traction surfaces to compensate for the imposed limits on pin travel. Figure 4, thus, represents a *slip-friction* embodiment of the CLT isolation system.

Friction between timber and steel introduces most of the uncertainty in the illustrated rocking schemes. The scheme of Figure 3 requires a high friction coefficient

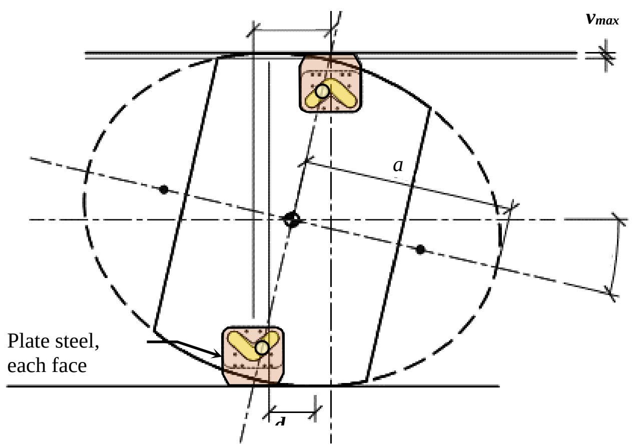

Figure 3: *Traction Rocking with Curved Slot*

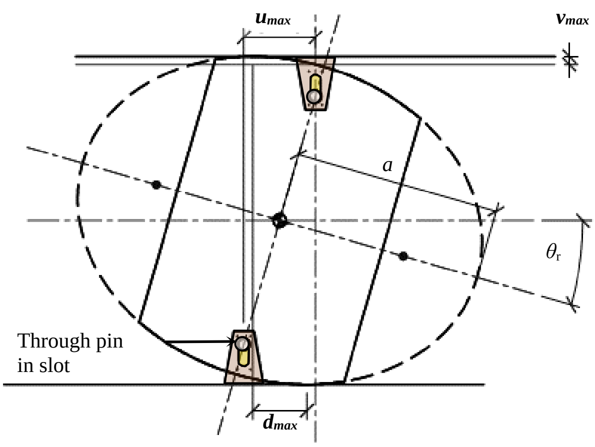

Figure 4: *Slip-Friction Rocking with Vertical Slot*

between timber and steel contact surfaces, because inadequate traction would allow the panel to slip. The vertically slotted connection of Figure 4 requires only a modest amount of friction, because the large-diameter steel pins transfer force through pipe bushings embedded in the timber. In fact, too much friction places the pin connection of the slip-friction configuration at risk of overload.

Several studies have examined the frictional contact between wood and steel, but deciphering a coefficient of friction for application presents contradictions. McKenzie and Karpovich reported friction coefficients, for 28 timber species, depending on wood moisture content, surface roughness of steel, and speed of sliding [32]. Balsam fir with moisture content between 10 and 14 percent, moving at slow speeds in the range of 0.2 to 0.5 mm/s, reportedly produced friction coefficients of 0.14 and 0.56 when respectively in contact with smooth and rough steel [32, p. 143]. Distinctly different friction coefficients, depending primarily on the surface roughness of steel, led McKenzie and Karpovich to conclude that steel must be impractically polished in order to reduce friction. Guan et al. made the opposite conclusion, stating that rougher steel surfaces produced lesser surface contact and lower friction coefficients [33]. Scaled physical models showed that each of the connection configurations, *no-slip traction* rocking of Figure 3 or *slip-friction* rocking of Figure 4, was feasible. Steel connections for each rocking mode were subsequently made to resolve the friction dilemma in full-scale tests.

2.3 DESIGN OBJECTIVES

The overarching project objective aims to increase demand for CLT in seismic applications, by developing a resilient, economic, and versatile soft-storey system using load-bearing CLT wall panels as isolators.

2.3.1 Resiliency

Resilient characteristics of the isolation system must exhibit:

- High lateral displacement capacity,
- Self-equilibrating mechanisms to minimize residual displacements,
- Durability over many cycles,
- Low natural frequency and long effective periods to limit magnitudes of seismically induced forces,
- Sufficient damping of oscillations, and
- Adequate resistance to wind with a reliable trigger to soften the lateral system in case of an earthquake.

Compliance with the seismic isolation “Chapter 17” of *ASCE/SEI 7-16* provides the most expedient path to resilient performance, within the existing framework of building codes [16].

2.3.2 Economy

CLT as an isolation system achieves cost-effective performance by:

- Averting damage to panel corners,
- Passively tapping into the potential energy of superstructure weight, instead of active post-tensioning, and
- Leveraging digital fabrication processes prevalent in the mass timber and steel industries.

Computer Numerical Control (CNC) routing and plasma cutting respectively realized the curved profiles at the load-bearing edges of CLT panels and slots in 12-mm thick steel plates.

2.3.3 Versatility

Versatility is achieved by:

- Varying the geometrical proportions of six ellipses, in order to tune the natural frequency and reciprocal effective period, and
- Varying frictional damping with two types of shear transfer connections that induce either *no-slip traction rocking* or *slip-friction rocking*.

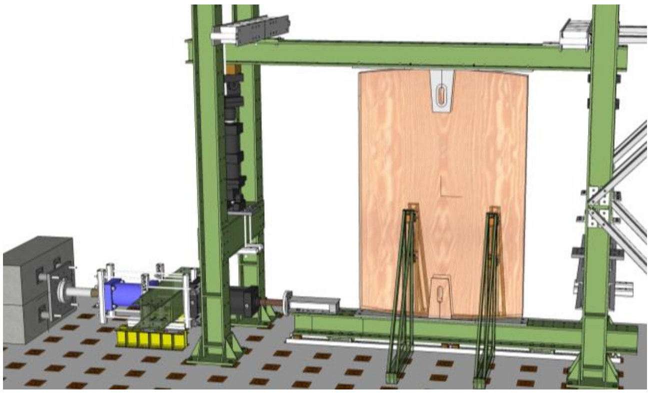

Figure 5: *Rocking wall test apparatus*

3 GLOBAL BEHAVIOUR

Figure 5 illustrates the full-scale validation test setup, used to quasi-statically determine the isolation properties of CLT panels. Two vertically oriented actuators simulate the gravity loads from superstructure. Individually, loads in each individual actuator vary depending on position of the contact points between the CLT panel and steel beam tracks. Overall, however, the pair of vertical actuators maintain a constant sum of overburden load. A pair of horizontally oriented actuators, shown in the left portion of Figure 5, work in series, in order to achieve the high stroke requirements of cyclic testing protocols. Two industrial rollers, each rated for 34 metric tons and guided within a channel track, enable the bottom beam to translate horizontally. The top beam raises and lowers during CLT panel rocking, by riding spherical bearings placed between the grey beams of Figure 5 and the columns.

3.1 CYCLIC PROTOCOL

Ideally, seismic isolators should be tested dynamically, in order to simulate various effects that might change with rates of loading. The *ASCE/SEI 7-16* standard, however, recognizes that limitations of common equipment and offers a quasi-static protocol, which requires more cycles than dynamic testing [15, 16]. Table 2 lists the displacement steps as percentages of the maximum displacement, $\boldsymbol{D_M}$. The procedure begins with 20 low-amplitude cycles to determine the properties of the isolation system under wind-level drifts. The number of cycles in the last step of the procedure depends on site-specific spectral design parameters and damping factors, according to Equation (1):

$$\frac{30 S_{M1}}{S_{MS} B_M} \geq 10\ cycles \qquad (1)$$

where S_{M1} = Maximum Credible Earthquake (MCE), 5% damped, spectral response acceleration parameter at a period of 1 s adjusted for site class effects, S_{MS} = Maximum Credible Earthquake (MCE), 5% damped, spectral response acceleration parameter at short periods adjusted for site class effects, and B_M = numerical coefficient tabulated on the basis of effective damping percentage, β_M [16, p. 177]. Note that B_M = 1.0 for systems with 5% effective damping, and spectral accelerations values for seismicity in Portland, Oregon, served this qualification round of testing.

Table 2: *Cyclic protocol for quasi-static lateral test*

Displacement Step	Number of Cycles
$0.25h_s$	20
$0.25D_M$	3
$0.50D_M$	3
$0.67D_M$	3
$1.00D_M$	6
$0.75D_M$	18

where h_s = storey height of 3.66 metres, and D_M corresponds to the displacement capacity of each panel specimen, as listed in Table 3.

Six 5-ply CLT panels, produced according to North American manufacturing standards for visually graded lumber, make up the initial round of testing specimens [34]. Thickness of the 5-ply varies from 167 mm to 175 mm, but insignificantly, as a result of modifications to manufacturing between production runs. Each CLT specimen varies in ellipse semi-major axis width, as listed in Table 3, left column. Ellipse minor axis height, 2*b*, remains constant at 3.66 m, in order to provide a consistent clear-storey height. Panel widths, furthermore, remain constant, at 2.44 m, for practicality of construction. The displacement capacity values listed in the middle column of Table 3 estimate the safe range that panels may travel laterally, before damaging the corners. The force magnitudes listed in the right column of Table 3 predict the lateral force required to reach displacement capacity, while supporting a maximum overburden of 400 kN. Calculations follow the

Table 3: *CLT panel specimen data*

Semi-major axis width, *a* (*mm*)	Displacement capacity, D_M (*mm*)	Max lateral force under max overburden (kN)
2350	864	77.0
2667	864	116
3188	737	166
3810	530	197
4407	394	220
5486	247	227

derivations of Londhe and Jangid, which use elliptic integral tables to solve equations [26]. The force estimates correspond well with *no-slip traction rocking*, pictured in Figure 3, but lateral forces increase with the vertically slotted connection of Figure 4. Horizontal connection constraint effectively pushes the panel through additional lateral displacement, and friction along the load-bearing edges of the panel adds force as panels must slip to complete the rocking motion. The test matrix, therefore, includes six specimens in two different connection configurations to determine whether a *slip-friction rocking* mode presents a viable alternative *to no-slip traction rocking*, for increased damping.

Because the magnitude of overburden load might affect ability of a CLT panel to simultaneously sustain lateral loads, each specimen must undergo the cycle protocol of Table 2 three times under low, medium, and high overburden of 133, 267, and 400 kN [16]. Six specimens times 2 connection types per specimen, times three levels of overburden, yields a test program of 36 quasi-static cycle protocols.

3.2 INITIAL HYSTERESIS RESULTS

To date, five of the six CLT specimens have been tested to chart the load-displacement properties through a range of up to 430 mm in each direction, nearly 860 mm of total stroke. The three plots of Figure 6 represent the hysteresis performance of the specimen with the least lateral stiffness, i.e. narrowest ellipse. The specimen has sustained over 60 low-amplitude cycles, 9 cycles at 25% lateral drift capacity, and 9 cycles at 50% lateral drift capacity. The plots of Figure 6 each represent a third of the total 78 cycles tested on the specimen to date, under low, medium, and high (133, 267, and 400 kN) overburden. Initial results look promising, because the plots retrace previous cycles, showing little to no signs of stiffness degradation thus far. Damping appears to increase with higher overburden, along with the slope of the load-displacement curves.

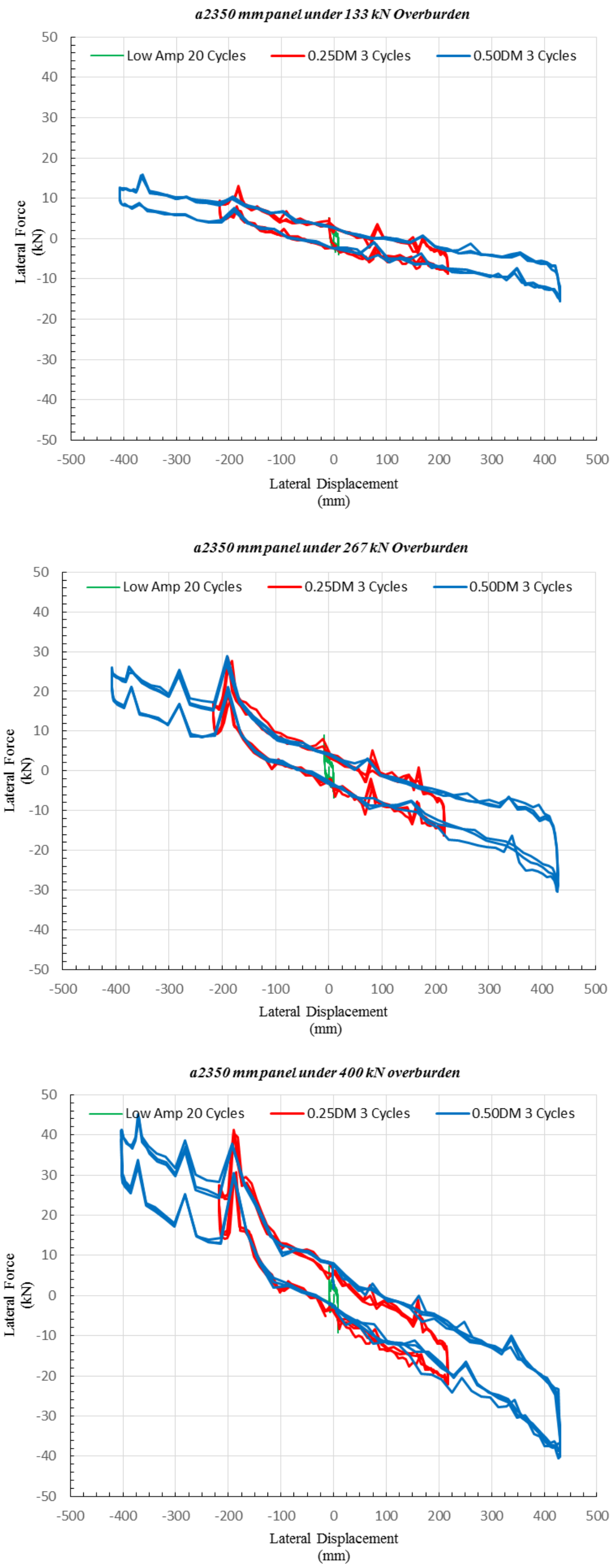

***Figure 6:** Hysteresis of a = 2350 mm CLT specimen* Initial

Estimates of the effective period for the least stiff specimen in the test program (*a* = 2350 mm) give a glimpse of how CLT can practically perform as an isolator. Equation (2) estimates the effective period at maximum displacement, T_M, according to the isolation standard:

$$T_M = 2\pi\sqrt{\frac{W}{k_M g}} \qquad (2)$$

where W = effective seismic weight of the structure above the isolation storey, k_M = effective stiffness of the isolation system at maximum displacement, D_M, and g = acceleration caused by gravity [16, p. 173]. Using partial hysteresis plots of Figure 6 to compute k_M, an effective period of approximately 4.5 seconds appears to be the longest effective period practically achievable by this CLT system of isolation. The remaining 5 specimens in the test program are geometrically stiffer than the narrowest ellipse. Geometry primarily dictates the effective period, which is characteristic of pendulum isolation systems.

Upon completion of the cyclic protocols designed for each specimen, detailed determination of effective stiffness (k_M), period (T_M), and damping (β_M) will be conducted in accordance with the isolation standard. Results thus far demonstrate that CLT panels will pass the standard specimen adequacy checks for stiffness degradation [16]. Analysis of the hysteresis plots will yield design properties for subsequent use in engineering isolated buildings.$T_M = 2\pi\sqrt{\frac{W}{k_M g}}$ (2)

4 MATERIAL EFFECTS

Hysteresis data defines the overall in-plane lateral stiffness of the panels, for prime engineering value, while a series of tools characterizes the contact behaviour of the CLT material. Figure 7 plots the surface strains of a rocked panel, using Finite Element Analysis (FEA) contact formulations. *Normal Lagrangian* contact elements impose zero-penetration constraints and, therefore, appropriately simulate the interface between steel and timber [35]. The Digital Image Correlation (DIC) plot of Figure 8, illustrates actual contact deformations that resemble the highlighted region of the Figure 7 FEA diagram. The DIC plot filters out rigid body movement, to focus on material deformations. Comparing a series of correlated images, furthermore, reveals where localized residual damage has occurred in the surface laminations.

Qualitative comparisons between the widest and narrowest elliptical profiles show that stiffer panels suffer local damage sooner than panels with more aggressive curvilinear cuts. Higher traction forces place timber in the outer laminations under significant local stresses perpendicular to grain. Wood splits as a consequence, but cross laminations restrain the crack widths, much like reinforcing bars restrain cracking in concrete. Local splintering of face laminations has occurred in a few CLT specimens, simply because of minor misalignment of the test apparatus, but chamfering the panel edges has since reduced splintering by improving the out-of-plane tolerance of panels. Out-of-plane flexibility of the system is critical to preventing damage to CLT panels in real building arrangements, which must orient panels orthogonally for effective isolation in all directions.

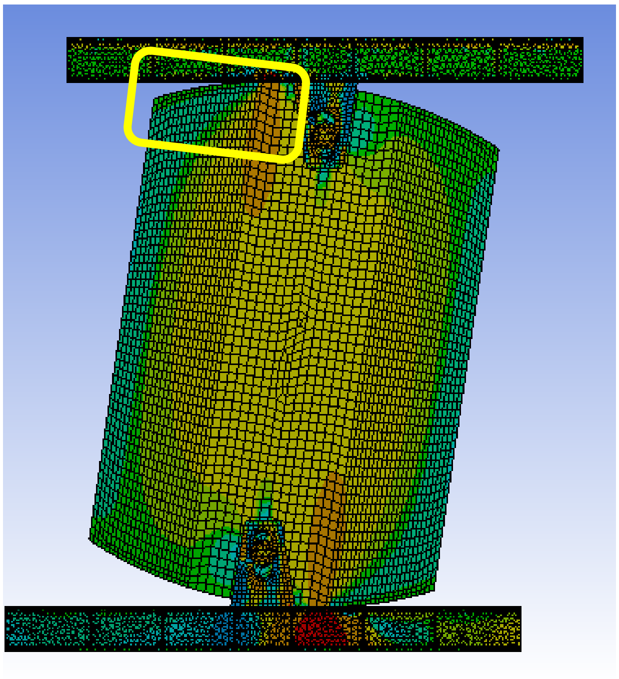

Figure 7: *Finite Element Analysis of contact behavior*

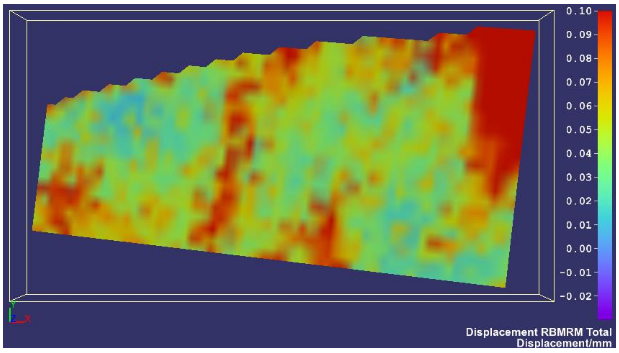

Figure 8: *Digital Image Correlation plot of wood deformations*

5 CONCLUSIONS

Elliptical profiles primarily engender CLT panels with isolation and self-centring properties. Slot shape of the pinned steel connections and the magnitude of friction at the load-bearing contact surfaces, moreover, drives the wall system into rocking subcategories. *No-slip traction rocking* produces the most effective form of seismic isolation, because the steel-to-timber connection serves only as a *displacement restraint* leaving the panel to rock most unencumbered. *Slip-friction* rocking places horizontal *constraint* on the steel-to-timber connections, which increases stiffness of the system, but adds frictional damping and an active shear transfer mechanism away from the contact points between panels and beam tracks. Each rocking behaviour offers distinct advantages that vary the balance of isolation and damping, for customization of multi-storey designs.

5.1 GLOBAL BEHAVIOUR

At a system level:

- Wider parent ellipse geometry makes CLT panels more stable and reliable in self-centring at lower levels of lateral displacement,
- Narrower parent ellipse geometry transforms CLT into more effective isolators,
- Frictional contact between wood and steel mainly drives the system performance, affecting the key properties of effective stiffness, period, and damping, and
- Effective period of approximately 4.5 seconds presents a practical limit for the system. Narrower ellipses, with lower eccentricity, will not likely self-centre to negate residual displacements.

5.2 MATERIAL BEHAVIOUR

Cross-laminated timber exhibits mostly elastic behaviour in the rocking wall application, except for localised damage in contact regions. Damage can be mitigated by:

- Limiting the traction forces that develop between load-bearing panel edges and track, and
- Chamfering the panel faces along the load-bearing edges to make panels more tolerant to out-of-plane misalignment.

5.3 NEXT STEPS

- Complete cyclic load protocols,
- Analyse hysteresis data for qualification, according to isolation standard provisions,
- Characterize the local damage of high-pressure timber contact, and
- Exemplify the efficacy of CLT isolation in an archetypal structural arrangement.

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