
Dissipating diaphragm joints – A novel approach for resilient mass timber structures.

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ABSTRACT

A lateral load-resisting system (LLRS) for a Mass timber structure requires energy dissipation in connections. Cross Laminated Timber (CLT) walls are one of the most used and researched LLRS concepts for mass timber structures. Since the ductility of CLT walls is restricted to the connections at the base, research has indicated that rocking action is observed in most pragmatic design situations, restricting the aspect ratio of ductile walls to 3 or higher .

Recently researched resilient LLRS concepts with CLT walls employ energy dissipation devices as hold-downs or couplers. Hold-downs are suitable for dissipating energy corresponding to the first-mode shape. The inherent flexibility of tall mass timber structures poses a challenge for engineers due to undamped higher-mode effects. Further, the issue of displacement incompatibility in rocking walls restricts their use as gravity load transfer systems.

To address these concerns, this paper presents a novel approach to connecting the diaphragm to the walls using dissipating diaphragm joints. This approach allows unrestricted gravity-load transfer, overcoming limitations imposed by aspect ratio. It significantly tackles shear forces induced by higher modes by damping individual storey displacements rather than lower resultant deformation at the base of the coupler.

The paper presents results from selected archetype structures designed for high ductility. Structural resilience is verified through nonlinear time-history analyses, complemented by a proof-of-concept experimental investigation conducted on a full-scale two-storey CLT building. The combined numerical and experimental results demonstrate displacement compatibility between the lateral load-resisting system and the associated gravity system, thereby validating the proposed concept.

1 INTRODUCTION

Mass timber is increasingly preferred for engineered buildings for its sustainability, eco-friendly characteristics, lightweight properties, and efficient construction capabilities. Cross Laminated Timber (CLT), with its low cost and bidirectional properties, has been extensively researched in the last two decades [1], [2], [3]. CLT serves dual roles as a vital building component and a Lateral Load-Resisting System (LLRS), particularly in its function as a wall.

1.1 Seismic design concepts with CLT walls

CLT wall as LLRS behaves rigidly [4] with ductility and damage restricted to the base/ connections. Various conventional and Low Damage Design (LDD) options have been researched.

The conventional systems include CLT walls with conventional hold-downs and couplers are prone to damage and result in pinching hysteresis and stiffness degradation [4], [5] and [6]. Further, these systems can have either rocking or sliding mechanisms, with most pragmatic aspect ratios with high ductility tending to be dominated by rocking behaviour. Furthermore, the rocking behaviour has displacement compatibility issues with connecting diaphragms [7].

LDD design concept in CLT walls includes walls with Post-tensioned (PT) cables [8], [9] and wall systems with resilient dampers and couplers [10], [11], [12].

Rocking CLT walls with PT cables requires CLT to be machined for PT cables to pass through and may require monitoring of PT force (long-term creep in timber), which may reduce the system's competitiveness [13].

The latter concepts of shear walls with resilient hold-downs and couplers are free from hold-down damage and limitations in PT force yielding and monitoring, and exhibit higher damped responses. These systems also require walls to be vertically decoupled from the gravitational system to avoid incompatibility with displacement.

A decoupled approach, investigated and tested by Moroder et al. (2014), lacks the advantage of gravity load transfer to the wall and the stiffness contribution to the Lateral Load-Resisting System (LLRS) from these loads. The limitation of the stiffness contribution was partially addressed by [14] through their low-damage floor diaphragm connections.

To address the above limitations of restricted wall aspect ratio, displacement incompatibility between wall-diaphragm, and utilisation of walls for gravitational load transfer in ductile design, a novel concept of dissipating diaphragm joint is developed and being investigated.

2 PROPOSED CONCEPT – DISSIPATING DIAPHRAGM JOINTS.

The proposed concept of Dissipating Diaphragm Joints (DDJ) uses controlled gravitational friction coupling combined with an established self-centring energy dissipator (RSFJ) to transfer horizontal forces to the CLT wall. The wall and hold-downs are capacity-designed for the shear and moment generated by the DDJ at various levels and remain elastic.

The ductile storey shear is resisted by friction between the diaphragm and the wall, through a controlled friction-slip surface attached to the top of the ledge/bottom of the diaphragm. The RSFJs are tuned to take care of the balance-storey shear and to ensure the slip is above SLS forces. Further, the RSFJs ensure that the diaphragm is self-centred after the earthquake, dissipating additional energy, resulting in a low-damage ductile design.

In most cases, the tributary mass on the CLT walls, acting as the Lateral Load-Resisting System (LLRS), will significantly exceed gravitational loads on the wall. Since the storey shear (V_i) is managed through a combination of forces in the self-centering energy dissipator (F_{RSFJ}) and friction force (F_F). It is important to

note that there may be conditions where the tributary mass (m_i) of the i^{th} storey is nominally reduced, while the live load in the considered bay of LLRS experiences a significant reduction. Therefore, the RSFJ force (F_{RSFJ_i}) should be tuned for larger forces. The storey shear of the i^{th} storey (V_i) must adhere to Equation 1.

$$V_i = F_{fr} + F_{RSFJ} \quad (1)$$

Where the design friction force F_{fr} is defined by equation 2

$$F_{fr} = \mu (0.9G_{ij}) \quad (2)$$

Where G_{ij} is the permanent actions on the i^{th} storey for the j^{th} wall.

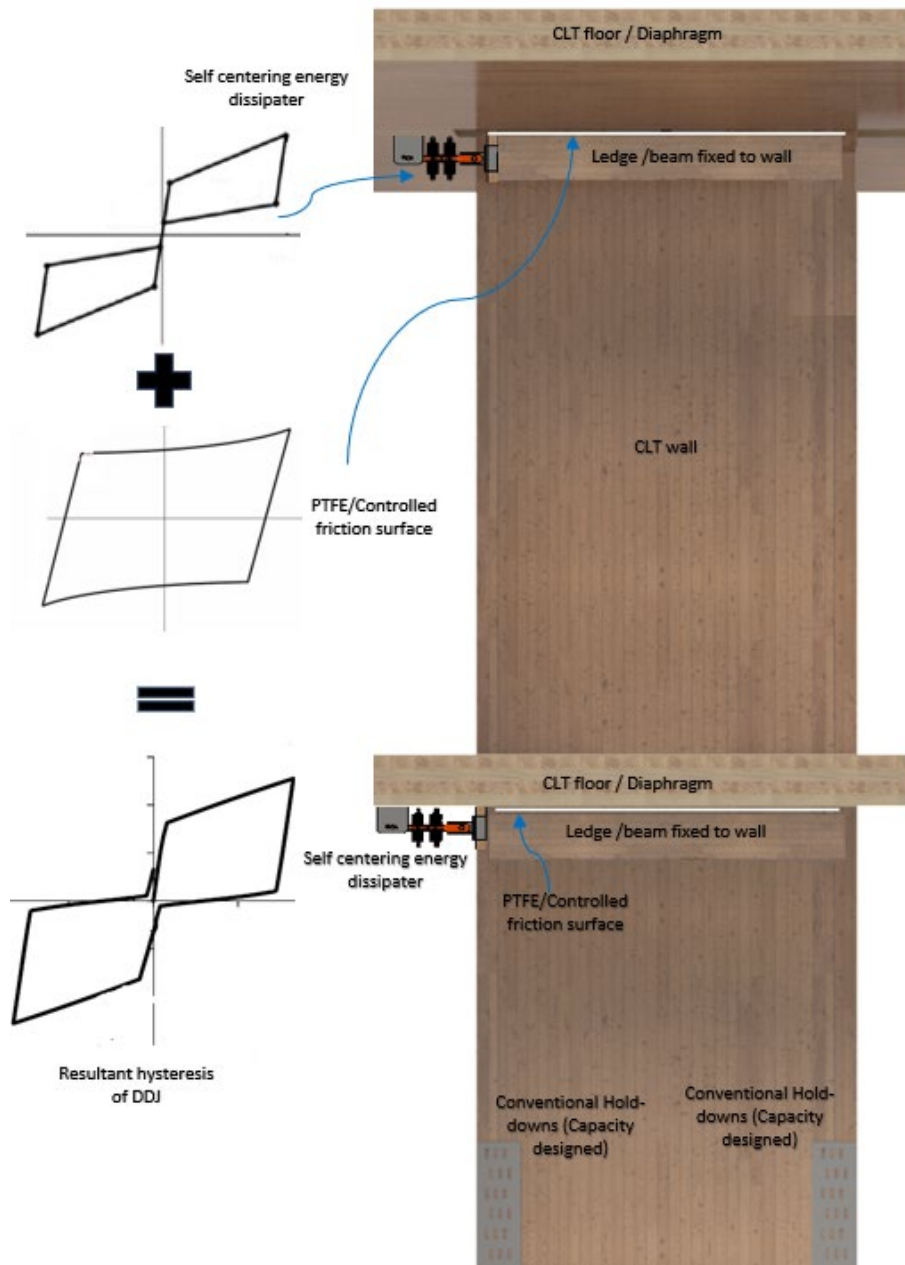


Figure 1 Proposed concept – Dissipating diaphragm joints

While conservatively for design purpose the contributory mass on the wall m_{ij} remains the full combination of dead loads, appropriate live loads and other loads.

The out-of-plane connections of the self-centring friction dampers are designed with a swivel joint to allow rotation, while the nominal rocking of the gravitational system would be consistent with the wall's elastic deformations.

2.1 Resilient slip friction joint RSFJ

Resilient slip friction Joint (RSFJ) is a self-centring energy dissipator developed in New Zealand by Zarnani and Quenneville [15]. These devices comprise of inclined sliding surfaces clamped with strong disc springs. The relative movement of the surfaces dissipates energy through friction while storing a portion of it as potential energy in the disc spring, thus creating a restoring force that drives the system back to its original position.

This system was selected due to potential residual displacements after an earthquake in the considered system. The RSFJ serves to restore the system to its original position while dissipating energy and preventing slip before the Serviceability Limit State (SLS). Furthermore, the system was chosen for its secondary fuse backup, which provides 1.5 to 2 times the design displacement with a low overstrength factor of 1.35. Tested and analytically validated by Hashemi et al[16], the system is confirmed to maintain its self-centring capability, even in the secondary fuse stage, ensuring resilience and robustness beyond the design level.

3 ANALYSIS AND NUMERICAL VALIDATION

A 10-storey archetype from Agarwal et al [12] was chosen for analysis and numerical modelling of the concept. The chosen archetype building is a mixed-use building with a ground-storey height of 4.5 meters, while the subsequent storeys are 3.2 meters. The building plan dimensions were 14.7x22.8meters with 5 LLRS grids each with one wall system consisting of DDJ. The wall dimensions were 5.5 meters long by 315mm thick (7 equal layers). The seismic weights of the first, second, and third to tenth storeys was calculated as 1306, 1137, and 879 kN, respectively [17]. The diaphragm is assumed to be CLT floors (refer to Table 1).

Table 1 Building information of archetype buildings ([12])

Building dimensions	14.7x22.8 m	No. of LLRS grid	5 Nos with 2 coupled walls each
storey height 1 st	4.5 m	Wall length (10 storey)	3.5/4.5/5.5 m
storey height 2 nd	3.2 m	Wall thickness	315 mm (7 layers)
storey height 3-6 /8/10	3.2 m	Modal period (10 Storey)	0.86 sec
storey weight 1 st	1306 kN	Hazard factor Z	0.3
storey weight 2 nd	1137 kN	Soil type	D
storey weight 3-6 /8/10	879 kN	Diaphragm	CLT
Wall aspect ratio	High (6)	Gravity loads category	Low

3.1 Numerical modelling

The effective properties of the CLT were calculated assuming longitudinal layers as machine stress-graded sawn timber with a modulus of elasticity of 8 GPa (MSG8), and MSG6 in the transverse direction, based on the CLT handbook [18].

3.2 Numerical analysis and design

The structure was designed assuming a ductility of three ($K\mu = 3$). The capacity of the self-centring energy dissipator was grouped across the number of stories: 6 kN for storey 1 to 4, 14 kN for storey 5 to 7, 28 kN for storey 8 to 9, and 48 kN for storey 10. The coefficient of friction for the friction isolator was kept as 0.15. Both the self-centring energy dissipator and the seating for the friction surface were designed for 1.3 times the assumed Maximum Considered Earthquake (MCE) drifts of 2.5% [23]. Further, the dissipator at the first storey was tuned and stiffened to 68kN to control storey drift. A higher-capacity self-centring energy dissipator is required because the storey drift profile of the Lateral Load-Resisting System (LLRS) with DDJs closely resembles that of tall MRF frames. This similarity might have resulted in a concentrated drift at the first storey, necessitating a higher-capacity RSFJ to restrain the storey to the wall. This needs further investigation, and a design process needs to be developed.

A set of 44 high-magnitude, far-field ground motions specified by FEMA-P695 was selected for this study [24]. The records were scaled to ensure the median spectral acceleration at the fundamental period of the archetype matches the ULS spectra. A non-linear direct integration method with 2% constant modal damping model was chosen to avoid spurious forces, adequately represent higher modes in response, and dissipate energy in high frequencies, preventing numerical errors.

4 RESULTS AND DISCUSSION

The NLTHA results for LLRS with DDJ showed that the seismic force demands (base shear) align with the designed base shear. Apart from a few outliers, the average base shear of 303 kN for the 44 strong motions indicates minimal shear magnification due to higher mode effects, suggesting damping of mode shapes even due to higher modes (refer to figure 3a). The structural hysteresis for stories and energy graphs indicates non-pinning, non-degrading hysteresis with considerable damping (refer to figure 3b).

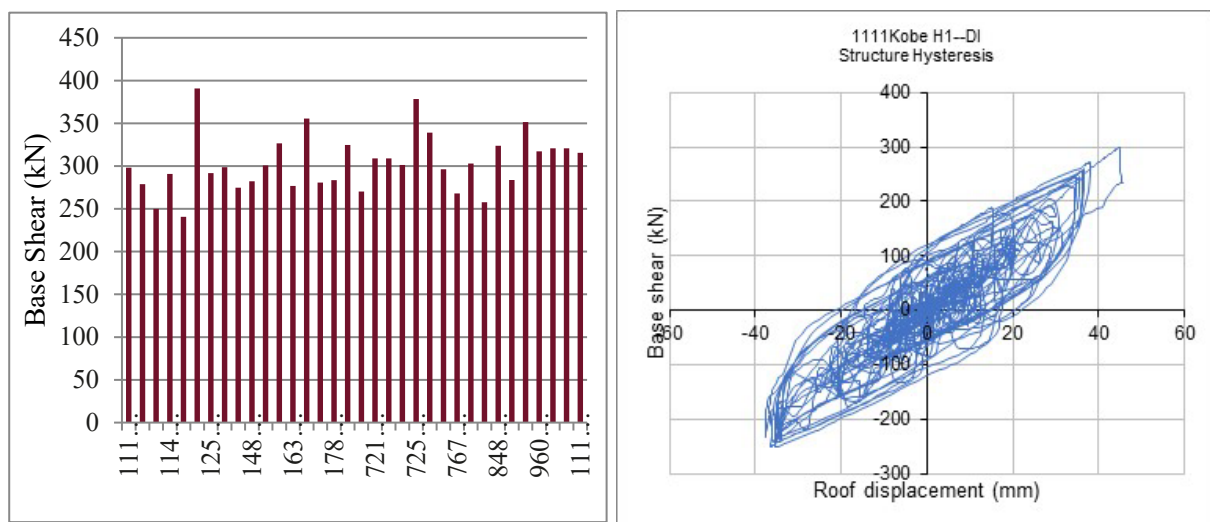


Figure 3 a) Base shear graphs for propped concept b) Structural hysteresis for RSN 1111 Kobe.

The storey drift profile complies with the design drift of 1.5%. The storey drift profile also indicates the effects of higher modes in the dynamic analysis (refer to Figure 4). However, these higher modes have minimal detrimental impact on the shear and moment profile of the wall (refer to Figure 5). Thus indicating that an efficient structure could be designed using DDJs.

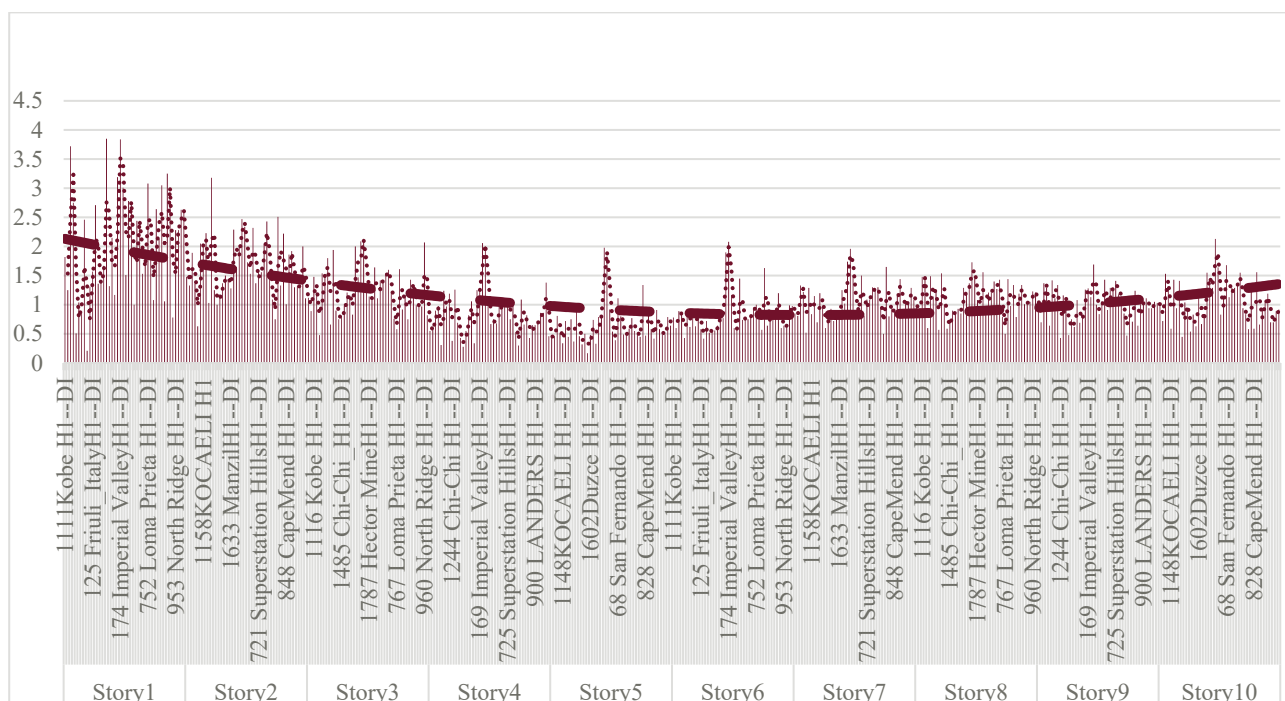


Figure 4 Storey drift and trendline for storey drift profile

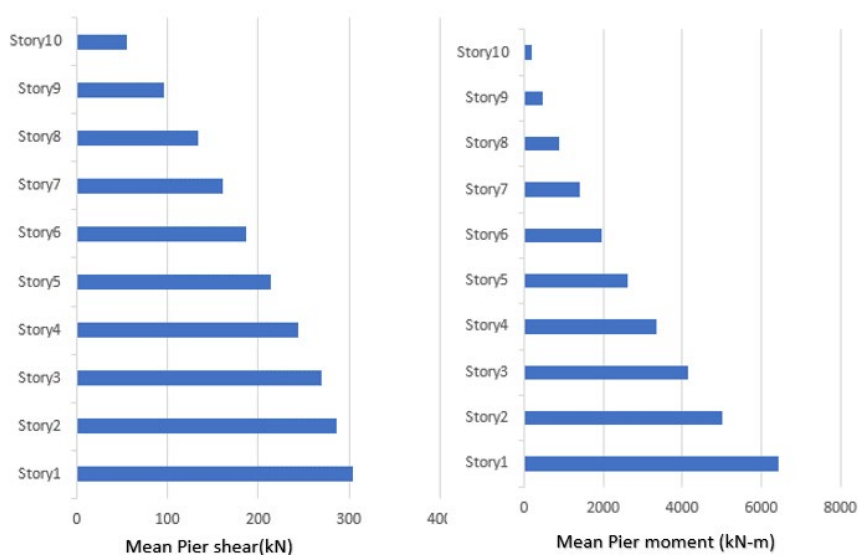


Figure 5 Pier shear (left) and Moments (right)

5 EXPERIMENTAL INVESTIGATIONS

A limited experimental investigation was conducted to validate the proposed concept using a full-scale, two-storey CLT building constructed at the University of Auckland. The structure comprised floor plans of 6.0 m by 3.5 m, with a storey height of 3.0 m. Two CLT walls located at the centre of the plan acted as the lateral load-resisting system in the longitudinal direction, while resilient tension bracing provided lateral resistance in the transverse direction (see Figure 1).

The floor diaphragm was supported by ledge beams on the walls and by point supports on columns. To represent gravity loading, 1.2 m-wide hollow-core slabs were placed on either side of the walls, resulting in a total seismic mass exceeding 10 tonnes for the test setup.

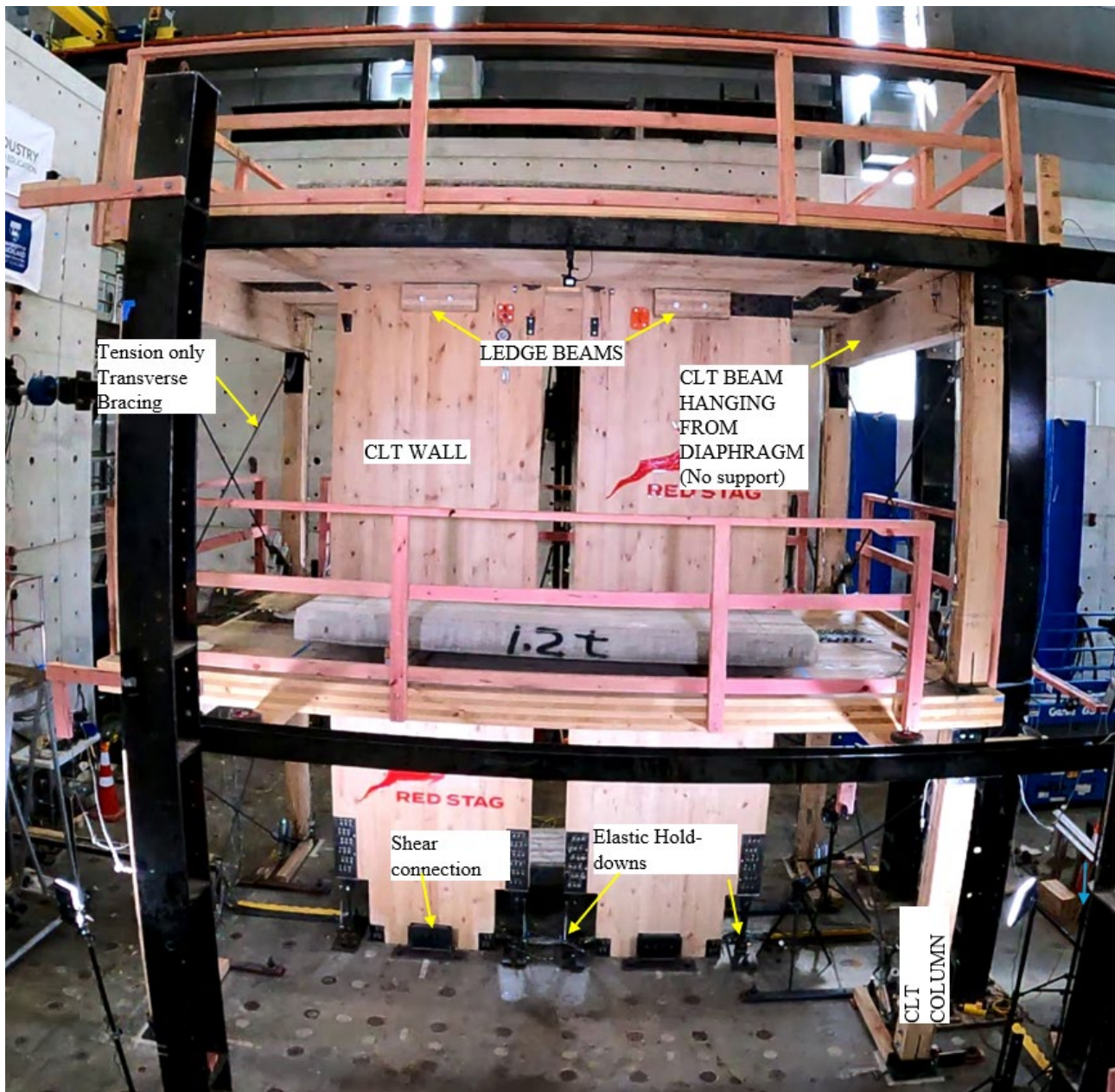


Figure 6 Test setup- at UOA lab

The structure was subjected to lateral loading up to 2.5% storey drift and subsequently unloaded to 1.5% drift to assess proof of concept and displacement compatibility between the lateral force-resisting system and the gravity load-resisting system (Figure 7). Self-centring resilient joints were not incorporated at this stage, and the structure was tested using ledge beams only.

The proposed concept demonstrated full displacement compatibility, with no observable wall rocking and no damage to the diaphragm or the gravity load-resisting system. The wall hold-downs remained undamaged

and did not yield, indicating no rocking at the wall base. The presence of a shear key, together with the lack of lateral deformation at the wall base, also eliminated sliding.

The force-displacement response exhibits stable hysteretic behaviour, with no evidence of sudden strength degradation, indicating robust load-transfer mechanisms throughout the test. The hysteretic response is approximately symmetric in both loading directions, suggesting balanced boundary conditions and uniform engagement of the load-resisting mechanisms. Despite the absence of self-centring resilient joints, the system exhibited measurable energy dissipation, primarily associated with frictional mechanisms. A slight post-slip stiffness was observed, which can be attributed to gravity load-carrying connections between the columns and the diaphragm, as well as the column base connections.

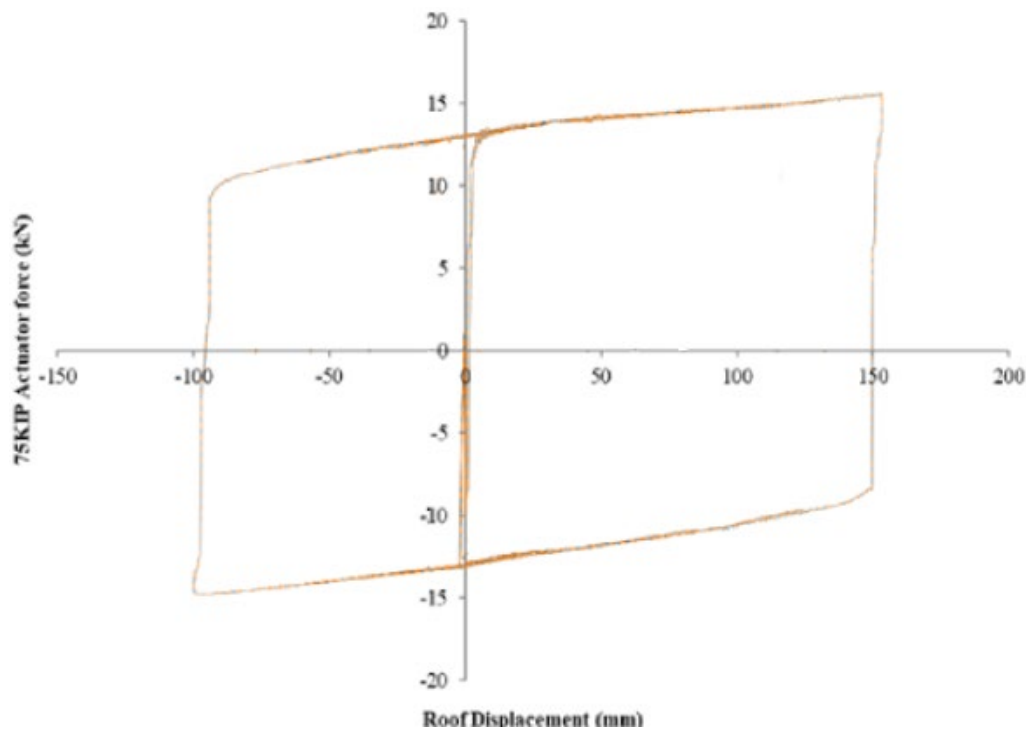


Figure 7 Roof Displacement vs Actuator force for the concept

6 CONCLUSION

The proposed innovative Dissipating Diaphragm Joints (DDJ) system showcases the potential for designing low-damage ductile high-rise mass timber buildings, particularly with balloon-type construction. It effectively addresses challenges associated with displacement incompatibility, potentially fostering increased adoption of sustainable mass timber buildings among developers and engineers. Furthermore, the absence of restrictions on the aspect ratio of walls in designing ductile structures provides more architectural freedom and efficiency.

A notable advantage is the damping of higher modes, as any storey movement generates damper displacement, effectively dissipating energy.

The resultant moment and shear force profile indicates that walls and connections could be designed more efficiently, given that connections account for a significant portion of the cost in timber structures. The expense of self-centring energy dissipaters can be offset by eliminating the cost of complex decoupling connections, utilising the wall as a gravitational system, and reducing the number of fasteners. Thus, the use of DDJ system can contribute to a resilient design with high efficiency.

Concerns related to self-centring are alleviated by incorporating self-centring energy dissipaters.

Experimental observations from the proof-of-concept testing demonstrated full displacement compatibility between the lateral force-resisting system and the gravity load-resisting system, with no observed damage to the diaphragm or gravity components, thereby confirming the fundamental viability of the proposed concept.

The proposed system shows potential for in-depth exploration through numerical, analytical, and experimental studies to instill confidence among design engineers for its utilization. The authors are planning a two-storey test for performance analysis and concept validation.

Overall, this study highlights the potential of using DDJs with balloon ductile CLT walls as an effective low damage seismic resistant system, and suggests the need for more comprehensive studies for the proposed concept.

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