Multidirectional cyclic testing of self-centering cross-laminated timber shear wall sub-assemblies

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ABSTRACT

Driven by demand for sustainable buildings and reduction in construction time, mass timber, specifically cross-laminated timber (CLT), is being more widely used in mid-rise buildings in the US. In areas of the US with a significant seismic (i.e. earthquake) hazard, mass timber buildings that are seismically resilient are of significant interest. Low damage post-tensioned self-centering CLT shear walls (SC-CLT walls) provide an opportunity to develop seismically resilient CLT buildings. There is however insufficient knowledge of the lateral-load response and damage states of SC-CLT walls under multidirectional seismic loading conditions, which can have a pronounce effect on the seismic resilience of buildings with SC-CLT walls. In order to fill this knowledge gap, a series of lateral-load tests were performed at the NHERI Lehigh Large-Scale Multi-directional Hybrid Simulation Experimental Facility to investigate the multidirectional cyclic behavior of a low damage, resilient three-dimensional CLT building sub-assembly with SC-CLT coupled shear walls, CLT floor diaphragm, collector beams, and gravity load system. Comparisons are made between the lateral-load experimental response of the SC-CLT walls under unidirectional and multidirectional cyclic loading.

1 INTRODUCTION

Cross-laminated timber (CLT) is an engineered wood structural component fabricated by laminating layers of timber boards in an orthogonal pattern, where the boards are glued together on their wide faces. Low damage post-tensioned self-centering CLT shear walls (SC-CLT walls) provide an opportunity to develop seismically resilient CLT buildings (Akbas et al. 2017, Ganey et al. 2017, and Pei et al. 2019). An SC-CLT wall is designed to allow gap opening between the base of the CLT wall panel and the foundation, when the overturning moment due to lateral forces is large enough to overcome the pre-compression due to post-tensioning, leading to a controlled-rocking response. Previous research focused primarily on the lateral-load response under unidirectional loading and analytical studies of isolated self-centering timber walls. The interaction of the SC-CLT wall with the adjacent building structural components, i.e. the floor diaphragms, collector beams, and gravity load system was not considered. A building's response under seismic loading is multidirectional and there are concerns that multidirectional loading may be more damaging to SC-CLT wall panels than unidirectional loading, affecting the seismic resilience of buildings with SC-CLT walls. This paper presents the results from an experimental study of the multidirectional lateral-load response of SC-

CLT walls within a timber sub-assembly. SC-CLT wall damage states are introduced and are qualitatively defined in terms of repairs needed to restore the lateral-load response of the wall. These damage states are based on visual observations of the test specimens.

2 EXPERIMENTAL PROGRAM

The cyclic lateral-load response of SC-CLT walls was investigated by performing a series of 0.625-scale quasi-static tests. The test sub-assembly, shown in Figure 1, consists of a multi-panel SC-CLT wall, a CLT floor diaphragm, glulam collector beams, and a glulam gravity load system (Amer 2023 and Sause et al. 2020). The multi-panel SC-CLT wall consists of two post-tensioned CLT wall panels (i.e. north and south, denoted NWP and SWP, respectively). Each CLT wall panel was post-tensioned with a 32 mm diameter PT steel bar that is anchored to the foundation. The two panels are connected with U-shaped flexural steel plates (UFPs) for energy dissipation. Two glulam collector beams are connected to the SC-CLT wall to transfer the in-plane lateral forces from the CLT floor diaphragm to the SC-CLT wall. The collector-beam-to-SC-CLT-wall connection consists of a round steel pin placed through a vertical slot in the wall that enables the CLT wall panels to rock without causing uplift of the collector beams and the floor diaphragm. The floor diaphragm is connected to the collector beams and the gravity beams using 6.35 mm x 203 mm Simpson Strong-Tie SDS wood screws. The CLT-floor-diaphragm-to-SC-CLT-wall connection consists of rubber bearings with sliding Teflon-to-Teflon interface, allowing free-rotation and uplift of the CLT wall panels and providing out-of-plane bracing to the SC-CLT wall. In the test setup, the CLT floor diaphragm does not represent a typical floor diaphragm, rather, is considered as test fixtures to transfer the applied forces from the actuators to the SC-CLT wall. More details of the test sub-assembly can be found in Amer (2023).

The multidirectional displacements of the test sub-assembly are specified and controlled at a structure-physical-node, denoted SPN (see Fig.1). The SPN is at a point in space at the top of the floor diaphragm and in the middle of the SC-CLT wall. The displacement degrees of freedom of the test sub-assembly are at the SPN. Multidirectional command displacements are imposed on the test sub-assembly to reach a predefined target floor diaphragm story-drift, denoted Θ_d^{target}. Continuous feedback from displacement sensors attached to the floor diaphragm provides the displaced positions of two measurement-structure-nodes (M_1SN at the north side of the wall and M_2SN at the south side of the wall, see Fig. 1). The feedback data is used to solve in real-time the non-linear kinematic equations to determine the SPN position during a test (Amer 2023, Sause et al. 2020, and Mercan et al. 2009). The test matrix consists of two specimens: unidirectional (UT), and multidirectional (MT) cyclic loading sub-assembly tests. In the UT, the test sub-assembly was subjected to monotonically increasing quasi-static cyclic in-plane loading up to a 6.0% floor diaphragm story-drift. In the MT, the test sub-assembly was subjected to the multidirectional loading protocol shown in Figure 2a, which follows a “bow-tie shaped” path (see Fig. 2b), consisting of 2 cycles of the bow-tie shaped loading path followed by a cycle in-plane loading at each amplitude of displacement up to 4.0% floor diaphragm story-drift.

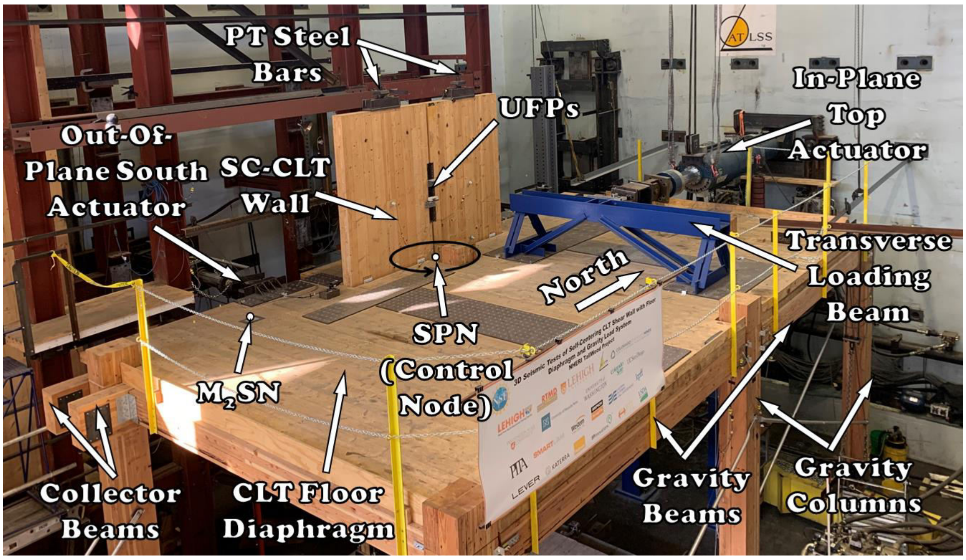

Figure 1: Isometric view of 0.625-scale test sub-assembly

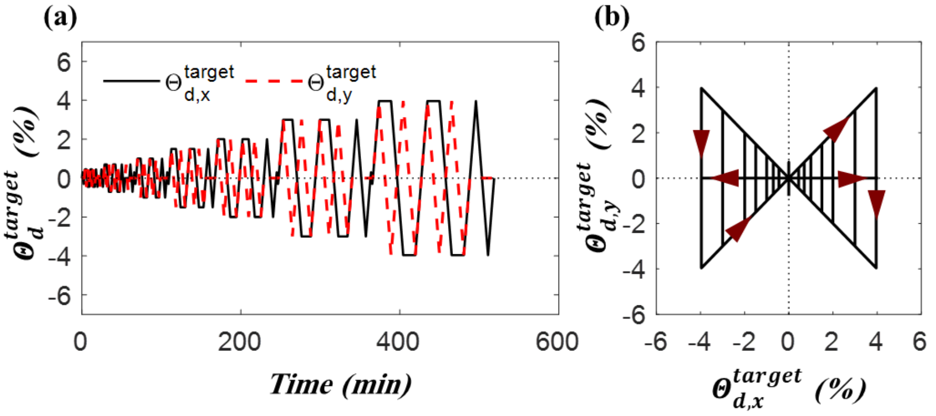

Figure 2: (a) MT time history of imposed in-plane and out-of-plane floor diaphragm story-drifts, $\Theta_{d,x}^{target}$ and $\Theta_{d,y}^{target}$, respectively; (b) associated multidirectional "bow-tie shaped" path

3 DISCUSSION OF LATERAL-LOAD TEST RESULTS

The SC-CLT wall damage states are qualitatively defined in terms of the repair actions needed to restore the lateral-load response of the wall to its initial state and are based on visual observations of the experimental results (Amer 2023). Table 1 summarizes the SC-CLT wall damage states, where they are illustrated in the photographs shown in Figure 3. The multi-panel SC-CLT wall has a total of eight corners. The eight wall corners were inspected when the lateral displacement of the test sub-assembly was at zero during each cycle of the loading protocol, and the damage is assumed to have initiated at the measured peak floor diaphragm story-drift corresponding to a specific cycle of loading. The damage states are quantified using engineering demand parameters (EDPs), which are representative of the lateral-load response of the SC-CLT wall (e.g. wall story-drift).

Table 1: SC-CLT wall damage states

Damage State	Damage Extent	Example of Damage Form	Repair Action
NLD	Minor or cosmetic	Fine compression splits	No repair needed
DS$_{I}$	Moderate	Initiation of outer ply delamination and/or buckling	Re-glue delaminated layers
DS$_{II}$	Significant	Excessive outer ply delamination and/or buckling	Add steel-plate reinforcement to CLT wall panel

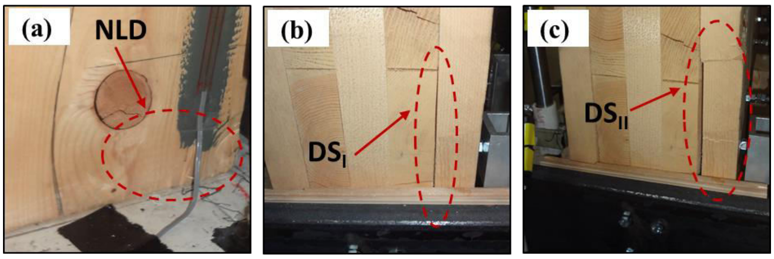

Figure 3: SC-CLT wall damage states: (a) fine compression splits (NLD); (b) initiation of outer ply delamination (DS$_{I}$); (c) excessive outer ply delamination and buckling (DS$_{II}$)

Table 2 lists the in-plane SC-CLT wall story-drift, $\hat{\theta}_{w,x}$, associated with the peak in-plane floor diaphragm story-drift when a damage state was first observed. The SC-CLT wall lateral-load response and the initiation of the SC-CLT wall damage states are shown in Figure 4 .The values of the EDP at the eight corners of the two panels of the SC-CLT wall exhibit variability throughout both tests. The experimental results show that multidirectional loading causes earlier (i.e. at a smaller story-drift) damage to the SC-CLT wall panels than unidirectional loading.

Table 2: Test results for first occurrence of damage

Damage State	**UT**			**MT**		
	CLT Wall Panel	$\hat{\theta}_{w,x}$ (%)	**Cycle Number**	**CLT Wall Panel**	$\hat{\theta}_{w,x}$ (%)	**Cycle Number**
NLD	NWP	0.41	3	SWP	0.24	1
DS$_{I}$	NWP	1.53	1	NWP	0.41	1
DS$_{II}$	SWP	3.13	1	SWP	2.04	1

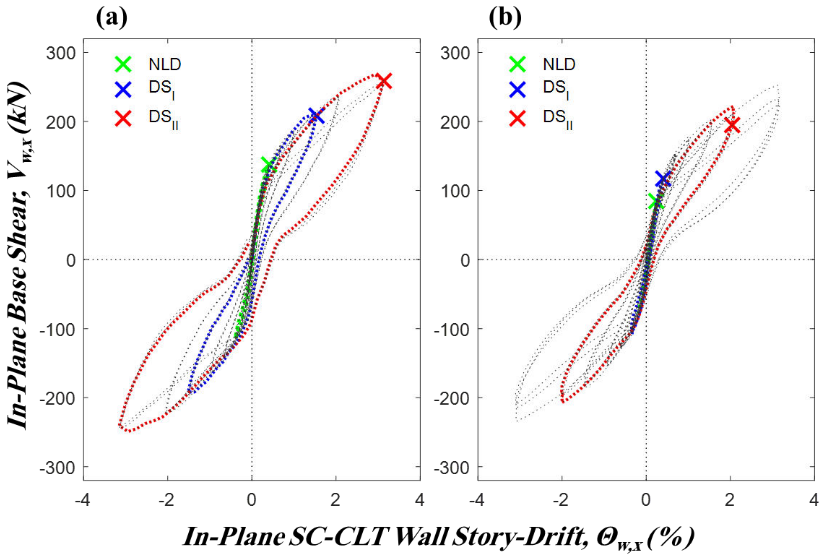

Figure 4: (a) In-plane lateral-load response and SC-CLT wall damage states initiation in UT; (b) in-plane lateral-load response and SC-CLT wall damage states initiation in MT

4 SUMMARY AND CONCLUSIONS

This paper presents the experimental results associated with the cyclic lateral-load response of 0.625-scale SC-CLT wall timber sub-assembly tests. Damage states are introduced to characterize the lateral-load response of the SC-CLT walls. The SC-CLT wall damage states are qualitatively defined in terms of the repair actions needed to restore the lateral-load response of the wall after the damage has occurred and are based on visual observations of the test specimens. The lateral-load response and damage of two SC-CLT wall test specimens, one tested under unidirectional (in-plane) cyclic loading and the other tested under multidirectional (in-plane and out-of-plane) cyclic loading, are presented and compared. The experimental results show that the initiation of an SC-CLT wall damage state occurs at smaller story-drift under multidirectional loading compared to unidirectional loading.

5 ACKNOWLEDGMENTS

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