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Multi-directional Cyclic Response of Self-Centering Cross-Laminated Timber Shear Walls

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ABSTRACT

This paper presents an experimental study on the multi-directional cyclic lateral-load response of post-tensioned self-centering (SC) cross-laminated timber (CLT) shear walls. The SC-CLT wall damage states are introduced and qualitatively defined in terms of the level of effort needed to repair the wall to restore its initial functional state. A comparison between SC-CLT wall damage states under unidirectional and multi-directional loading is presented. The experimental test results show that the SC-CLT wall damage state initiation occurs at lower story-drifts under multi-directional loading compared to unidirectional loading. The SC-CLT wall damage states are quantified in terms of the engineering demand parameter (EDP) defined as wall story-drift. Fragility functions that relate the conditional probability of the occurrence of a selected damage state at a wall corner to the EDP are developed. The results reinforce the observations that multi-directional loading on the CLT shear walls causes more damage that unidirectional loading.

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. Previous research, although focused primarily on unidirectional testing, showed that seismically resilient CLT wall buildings can be potentially achieved through low-damage post-tensioned self-centering (SC) CLT shear walls (SC-CLT walls) [1, 2]. Building response under earthquake is multi-directional and there are concerns that multi-directional loading is more damaging than unidirectional loading, affecting the seismic resilience of timber structures with SC-CLT walls. This paper presents the experimental test results associated with the multi-directional lateral-load response of SC-CLT walls of a 0.625-scale timber test sub-assembly. SC-CLT wall damage states are qualitatively defined in terms of the level of effort needed to repair the wall to restore it to its initial functional state. These damage states are compatible with visual observations of the experimental test results. Using the experimental test results, fragility functions that relate the conditional probability of the occurrence of a damage state to the SC-CLT wall story-drift, Θ_w, are established by

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estimating the likelihood that a wall corner reaches or exceeds a selected damage state.

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 Fig. 1(a), consists of an SC-CLT wall, a CLT floor diaphragm, glulam collector beams, and a glulam gravity load system [3, 4]. The SC-CLT wall consists of two post-tensioned CLT wall panels; which are north and south CLT wall panels denoted as NWP and SWP, respectively, that are connected with U-shaped flexural steel plates (UFPs) for energy dissipation. The multi-directional displacements of the test sub-assembly are specified and controlled at a structure-physical-node, denoted as SPN (Fig. 1(a)). The SPN is located at the top of the floor diaphragm, at the middle of the SC-CLT wall. The degrees of freedom of the test sub-assembly are associated with the SPN. Multi-directional command displacements are imposed on the test sub-assembly to reach a predefined target floor diaphragm story-drift, denoted as Θ_d^{target}. Real-time continuous feedback from displacement sensors, attached to the CLT floor diaphragm, are used to determine the displaced position of the SPN from two measurement-structure-nodes (M1SN at the north side of the wall and M2SN at the south side of the wall, as shown in Fig. 1(a)) [4, 5]. The test matrix consisted of two specimens involving unidirectional (UT) and multi-directional (MT) cyclic lateral loading tests. The test sub-assembly for UT was subjected to monotonically increasing quasi-static cyclic in-plane loading of 3 cycles up to 6.0% floor diaphragm story-drift. The test sub-assembly for MT was subjected to the multi-directional loading protocol shown in Fig. 1(b) consisting of 2 cycles of the bow-tie shaped loading path (Fig. 1(c)) with a cycle of in-plane loading at each amplitude up to 4.0% floor diaphragm story-drift.

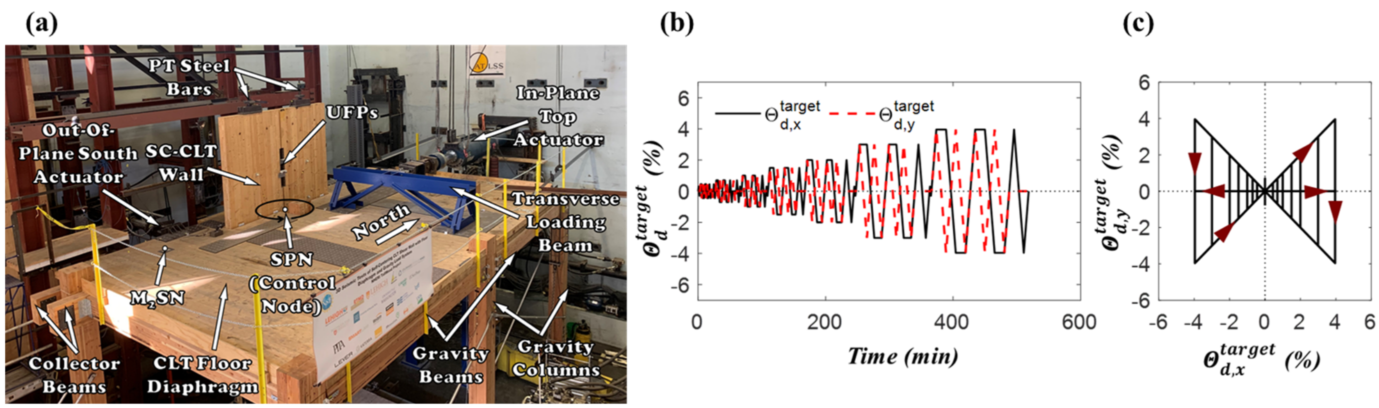

Figure 1. (a) 0.625-scale test sub-assembly; (b) multi-directional time history of imposed in-plane, $\Theta_{d,x}^{target}$, and out-of-plane floor, $\Theta_{d,y}^{target}$, diaphragm story-drift; (c) bow-tie shaped loading path

Discussion of SC-CLT Wall Test Results

The SC-CLT wall damage states are qualitatively defined in terms of the level of effort needed to repair a wall after damage has taken place, and are based on the visual observations of the experimental test results [3]. The objective of the repair is to restore the wall to its pre-earthquake functionality level. Table 1 and Fig. 2 summarize the SC-CLT wall damage states.

Table 1. SC-CLT wall damage states

Damage State	Damage Extent	Example of Damage Forms	Repair Extent
NLD	Minor or cosmetic	Fine compression splits	No repairs needed
DS_I	Moderate	Initiation of outer ply delaminated and/or buckling	Re-glue delaminated layers
DS_{II}	Significant	Excessive outer ply delaminated and/or buckling	Steel bearing plate attachment to the CLT wall panel

Since the SC-CLT wall inspection was conducted at the zero position of the test sub-assembly, the damage is assumed to have initiated at the measured peak in-plane floor diaphragm story-drift, $\Theta_{d,x,max}$, corresponding to a specific cycle of loading. The SC-CLT wall damage states are quantified in terms of an engineering demand parameter (EDP), which is the measured in-plane SC-CLT wall story-drift, $\Theta_{w,x}$, corresponding to $\Theta_{d,x,max}$, where a form of damage initiates [3]. The initiation of SC-CLT wall damage state is summarized in Table 2. Figure 3(a) and (b) compare the lateral-load response and shows when SC-CLT wall damage states initiate up to the target in-plane wall story-drift of 3.0%. These results indicate that the initiation of SC-CLT wall damage state occurs at lower story-drifts under multi-directional loading compared to unidirectional loading.

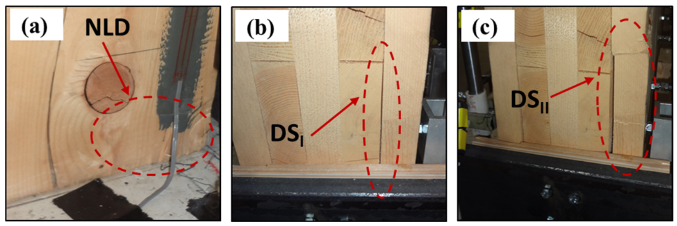

Figure 2. SC-CLT wall damage states: (a) fine compression splits (NLD); (b) initiation of outer ply delamination (DS$_{I}$); (c) excessive outer ply delamination and buckling (DS$_{II}$)

Table 2. Experimental test results of the initiation of SC-CLT wall damage states

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

The values of the EDP at the eight corners of the SC-CLT wall exhibits variability throughout both tests. Fragility functions of a component (i.e., wall corner) damage states are developed based on the experimental test results [3]. The fragility functions, formulated by using a lognormal cumulative distribution function (CDF), relate the probability of reaching or exceeding a selected damage state, ds_i, conditioned on the EDP (Eq. 1).

$$P(DS \geq ds_i |\ \mathrm{EDP} = \mathrm{x}) = \Phi(\frac{\ln(x)-\lambda}{\zeta}) \tag{1}$$

In Eq. 1, λ is the lognormal mean, ζ is the lognormal standard deviation, and Φ is the standard normal CDF. The geometric mean, $\bar{\lambda}$, which is equal to the exponential of λ, is calculated to determine the 50% probability of reaching or exceeding the selected damage state. Table 3 summarizes the estimated statistical parameters of $\Theta_{w,x}$ for component damage states.

Table 3. Estimated statistical parameters of $\Theta_{w,x}$ for component damage states

Parameter	**UT**			**MT**		
	NLD	**DS$_{I}$**	**DS$_{II}$**	**NLD**	**DS$_{I}$**	**DS$_{II}$**

$\bar{\lambda}$ (%)	0.91	2.28	3.49	0.67	1.27	3.05
ζ	0.542	0.320	0.182	0.618	0.589	0.206

Figure 3(c) shows the component fragility function conditioned on $\Theta_{w,x}$ corresponding to the SC-CLT wall damage states. The results in Fig. 3(c) show that for a given value of the EDP, $\Theta_{w,x}$, the probability of a wall corner reaching or exceeding a selected damage state is greater in MT compared to UT. The results reinforce the observations that multi-directional loading on the CLT shear walls causes more damage that unidirectional loading.

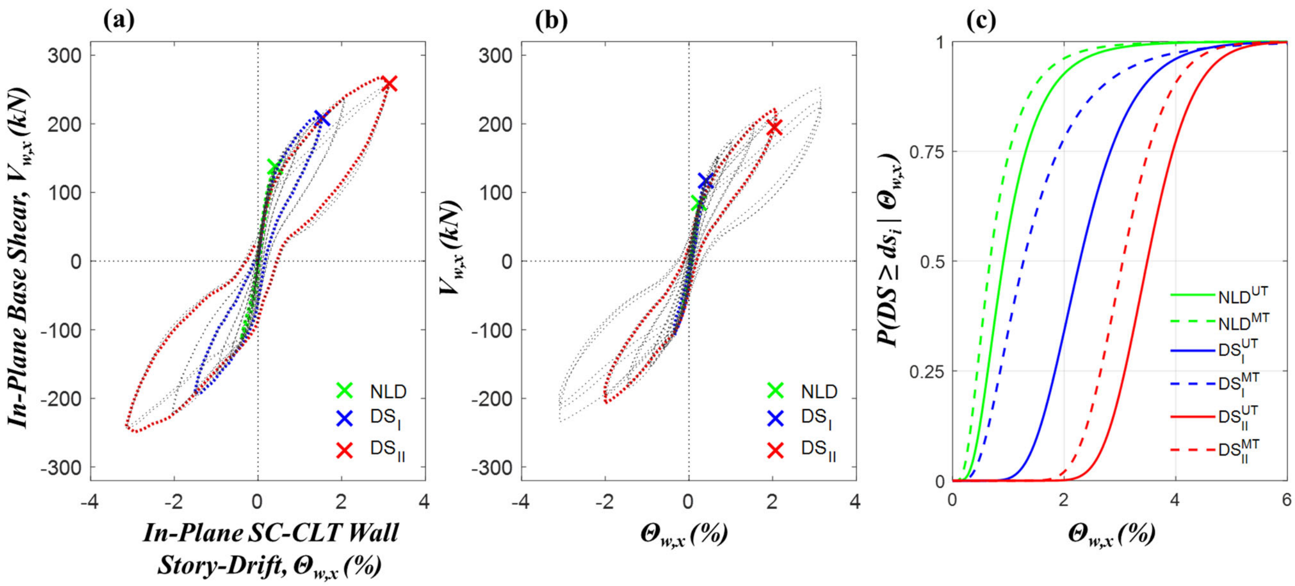

Figure 3. (a) In-plane lateral-load drift response and SC-CLT wall damage states initiation in UT; (b) in-plane lateral-load drift response and SC-CLT wall damage states initiation in MT; (c) Component fragility function conditioned on $\Theta_{w,x}$ corresponding to the SC-CLT wall damage states

Conclusions

This paper presented the experimental tests results associated with the cyclic lateral-load response of SC-CLT walls of a 0.625-scale timber test sub-assembly. Damage states are introduced to characterize the lateral-load response of SC-CLT walls. Two experimental tests are presented to compare the lateral-load response and damage states of SC-CLT walls under unidirectional and multi-directional cyclic loading. The initiation of an SC-CLT wall damage state occurred at lower story-drifts under multi-directional loading compared to unidirectional loading. Fragility functions conditioned on the in-plane SC-CLT wall story-drift, $\Theta_{w,x}$, are developed. The probability that a wall corner reaching or exceeding a selected damage state at a certain story-drift is larger when the wall is subjected to multi-directional loading compared to unidirectional loading. The results reinforce the observations that multi-directional loading on the CLT shear walls causes more damage that unidirectional loading.

Acknowledgments

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