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TESTING THE INFLUENCE OF SYSTEM EFFECTS ON THE LATERAL RESPONSE IN T-SHAPED WOOD FRAME SHEAR WALLS

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ABSTRACT: This paper examines the impact of transverse shear walls (TSW), out-of-plane bending stiffness of diaphragms (FDIA), and axial (gravity) loading (AXL) on the lateral response of strong wood-frame shear walls (SWs) in multistory light frame timber buildings (LFTBs). Experimental tests assessed the lateral cyclic response of T-shaped SW assemblies with and without diaphragms and gravity load. Tests showed that the TSW effect enhances the lateral stiffness and strength but reduces the deformation capacity. The FDIA and AXL effects further influence the stiffness and strength and compensate in part for the reduction of the deformation capacity due to the TSW effect. Diaphragms also made the T-shaped SW response more symmetrical and improved the evolution of secant stiffness, cumulative dissipated energy, and equivalent viscous damping as the lateral drift increases. Numerical analyses of a theoretical building model with T-shaped SWs showed significant reductions in lateral drift and uplift compared to those of Planar SWs alone, highlighting the importance of considering system effects in the seismic design of LFTBs.

KEYWORDS: System effects, non-planar, transverse shear walls, out-of-plane diaphragm stiffness, axial load.

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1 – INTRODUCTION

The lateral configuration of timber buildings is based on the fundamental principle that shear walls (SWs) are the only structural members that take lateral forces. These SWs are assumed to take in-plane lateral forces only (i.e., planar SWs), and any other structural member does not influence the lateral strength and stiffness of each SW. While this traditional assumption had limited implications in the past for the design of low-rise structures, it may significantly affect the design of contemporary and future mid- and high-rise timber buildings. Tests conducted on multistory timber buildings have revealed that the actual lateral stiffness of timber structures might be greater than the theoretical stiffness consistent with the aforementioned assumptions [1]. Possible reasons are the effect of gypsum wallboards [2] and system (coupling) effects from other structural members [1]. By system effects, we refer to the interactions of a planar SW with other structural assemblies that cause its behavior to deviate from the theoretical behavior of an isolated, cantilever planar assembly. In reality, the ability of SWs to bend freely is constrained by transverse shear walls (TSWs), out-of-plane flexural stiffness of diaphragms (FDIA), and axial (i.e., gravity) loading (AXL). This study aims to provide more insight into these issues by conducting experimental tests on T-shaped wood-frame SW assemblies, with and without diaphragms and with and without axial loading. This research focuses on system effects in a particular structural system, namely Light Frame Timber Buildings (LFTBs).

1.1 INFLUENCE OF TSWs

TSWs are crucial for lateral performance in LFTBs [3-5]. While past work explored their potential to replace hold-downs [6-10], few examined their full impact on SW behavior. Results show TSWs can significantly boost stiffness and strength. Collins et al. (2005) [11] and Foliente et al. (2000) [12] found major system effects from TSWs and roofs, influenced by connection details. Still, they reported little impact on hysteretic behavior [11-13].

Girhammar et al. (2008) [14] proposed an analytical method showing up to 100% lateral strength increase with TSWs for SWs with a 1:2 aspect ratio. However, it ignored out-of-plane stiffness, prompting calls for more testing—especially on "strong SWs" [15-17] used in seismic mid-rise buildings. These differ from conventional SWs by featuring enhanced framing, fasteners, and sheathing. Benedetti et al. (2022) [4] modeled TSW effects under AXL, showing TSWs reduce rocking motion at the building level, a detail not captured in simplified models.

CLT studies echo this importance [18,19]. Ruggeri et al. (2022) [19] found that TSWs can double the lateral capacity and significantly increase the stiffness of CLT SWs. Their influence depends on position, connections, and hold-downs, underscoring the need for stiff connections between SWs and TSWs to achieve composite action—an effect that requires further experimental validation.

1.2 INFLUENCE OF FDIA

FDIA also contributes to restraining SW overturning; however, this effect is not considered in current design standards. Bagheri et al. (2019) [20] demonstrated that most diaphragms possess sufficient out-of-plane bending stiffness to influence SW behavior. Nevertheless, existing analytical models [e.g., 3, 21–23] typically assume diaphragms to be infinitely flexible in the out-of-plane direction, thus neglecting this contribution. Further experimental and numerical investigations are necessary to quantify the FDIA effect.

Greater progress has been made in assessing FDIA effects within CLT systems. In non-planar CLT SW assemblies, the combined influence of FDIA and TSWs resulted in a 155% increase in lateral stiffness [18]. However, the individual contributions of each component were not separately quantified. Tamagnone et al. (2020) [23] reported that the impact of FDIA on planar CLT SWs was limited, primarily constrained by the stiffness of the diaphragm-to-wall connections. In contrast, D'Arenzo et al. (2021) [24] found that increased diaphragm interaction enhanced rocking stiffness and altered the overall kinematic response. These findings highlight that the role of FDIA in timber systems remains insufficiently characterized and warrants further investigation.

1.3 INFLUENCE OF AXL

AXL, resulting from gravity loads and overturning moments, has been shown to enhance the performance of SWs. Orellana et al. (2021) [25] reported increases of 141% in lateral stiffness, 37% in strength, 104% in equivalent viscous damping, and 55% in ductility due to AXL. Additionally, AXL reduced the fundamental period and increased the overall strength of the building. Despite these benefits, the interaction of AXL with other system effects—such as TSWs and FDIA—remains poorly understood. In CLT assemblies, AXL has been shown to diminish the effectiveness of TSWs [19], and in other studies [23], it altered the SW behavior from coupled to uncoupled. As with TSW and FDIA, AXL is a critical yet understudied parameter in the seismic response of timber structures.

2 – MATERIALS AND METHODS

To evaluate system effects—specifically, TSW, FDIA, and AXL—two full-scale SW assemblies were tested (see Figure 1). Each specimen measured 7.32 m in length by 5.1 m in width, replicating the ground-level configuration of strong wood-frame SWs in a seven-story residential building designed by the Chilean seismic code NCh433 [26]. One specimen was tested without a diaphragm to isolate the TSW effect (Figure 1-a), while the other incorporated a diaphragm to examine the combined influence of FDIA and AXL (Figure 1-b).

Both assemblies consisted of a non-planar T-shaped SW and an adjacent Planar SW. The T-shaped configuration included a central web SW (type A) and two perpendicular flange SWs (type B), while the Planar SW

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matched the type B configuration (as described in [27]). All SWs were constructed using 41×185 mm (2×8") C16 Chilean radiata pine studs, spaced at 400 mm following NCh1198 [28], and sheathed on both sides with 11.1 mm APA-rated OSB panels [29]. The framing incorporated double top and bottom plates, with connections detailed per SDPWS [21] using smooth-shank nails [30]. The connection between the flange and web SWs in the T-shaped assembly employed six SLOT90 connectors, chosen for their proven strength and ease of installation as evidenced in preliminary testing.

Figure 1. General configuration of the tested assemblies to evaluate the impact of: (a) TSW effect only; and (b) TSW effect + FDIA and AXL effects.

To investigate the FDIA and AXL effects, a T-shaped diaphragm—representative of typical light-frame timber building floors—was installed atop the SW assemblies (see Figure 1-b) This diaphragm was constructed from C16 Chilean radiata pine [28] beams and sheathed on both sides with 15.1 mm OSB panels [29], with construction details further documented in [27]. It was fastened using smooth-shank nails and Simpson screws at 100 mm spacing. The diaphragm configurations varied over the Planar and T-shaped SWs to replicate realistic construction scenarios.

Cyclic loading was applied using a bidirectional hexagonal protocol based on FEMA 461 [31] and the CUREE-Caltech procedure [32], with a reference displacement of 61 mm (0.25% of SW height) applied in both longitudinal and transverse directions. Two hydraulic actuators—with displacement capacities of ±200 mm and ±50 mm and force capacities of +588 kN and −294 kN, respectively—delivered lateral loads through the collector beam. The first specimen (without diaphragm, see Figure 1-a) was used to isolate the TSW effect. The second specimen (with diaphragm, see Figure 1-b) was tested in two phases: initially under combined FDIA and AXL conditions using axial rod tensioning of 85 ± 0.5 kN (resulting in end-stud compressive stresses below 20% of allowable limits), followed by full cyclic loading without axial force to isolate the FDIA contribution.

The test setup consisted of a reaction wall, a strong floor, and a steel reaction beam. Specimens were anchored using ϕ32 mm anchor bolts and laterally restrained to prevent sliding and out-of-plane instability. Out-of-plane bracing was not required for the specimen used to evaluate the combined effects of FDIA and AXL, as the diaphragm provided sufficient restraint. Instrumentation included 41 LVDTs, load cells at the reaction points, and sensors integrated into the actuators. Axial forces were measured using strain gauges attached to the threaded rods, while uplift was recorded with LVDTs positioned at the base of the specimens. This configuration enabled a controlled and systematic evaluation of the individual and combined contributions of TSW, FDIA, and AXL to the lateral response of strong wood-frame SWs. Additional details of the test setup are provided in [27].

3 – RESULTS

Both Planar and T-shaped SW assemblies exhibited consistent failure patterns, including nail pull-out, nail shear-off due to bending, and detachment of OSB panels from the wood frame—consistent with previous observations on strong SWs with continuous rod systems [16]. In the diaphragm specimen, additional failures were observed, including local OSB crushing at the diaphragm-to-wall interface and nail pull-out within the diaphragm itself. In the T-shaped assembly, concentrated stresses near the web-to-flange connection led to premature failures in the OSB-to-wood frame nailed connection, particularly on the right side of the web SW (i.e., type A, as described in [27]). To mitigate this, a denser nailing pattern is recommended. Damage to the wood frame was moderate, primarily affecting the central double studs, while the rod system remained elastic, as intended by design.

Backbone curves from cyclic testing (Figure 2) revealed notable differences between Planar and T-shaped SWs. The T-shaped SW exhibited asymmetric hysteresis in the longitudinal direction, attributed to the interaction between the web and flanges, and symmetric behavior in the transverse direction due to geometric symmetry.

The TSW effect enhanced performance compared to the Planar SW, increasing elastic stiffness by 19% and peak strength by 98%, although it reduced deformation capacity by 30% due to premature nail failure at the web-to-flange connection. At 0.2% and 0.4% drift levels,

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secant stiffness increased by up to 50% and strength by 40%, respectively, aligning with the current and proposed design drift limits for LFTBs in Chile [26,33].

The FDIA effect provided additional improvements. With the diaphragm installed, the T-shaped SW showed a more symmetric response, along with a 50% increase in peak strength and a 30% increase in deformation capacity relative to the Planar SW. Secant stiffness increased by 68% at 0.2% drift and 28% at 0.4% drift compared to the T-shaped SW without the diaphragm. However, in the transverse direction, FDIA had a limited effect, increasing peak strength by only 8%.

The combined FDIA + AXL effect resulted in the greatest performance gains. In the longitudinal direction, secant stiffness increased by 76% at 0.2% drift and 33% at 0.4% drift compared to the T-shaped SW without the diaphragm. Elastic stiffness increased by 162% for the T-shaped SW and by 66% for the Planar SW. These findings are consistent with previous studies on axial load effects in planar strong SWs [25] and underscore the diaphragm's more significant role in non-planar SW configurations.

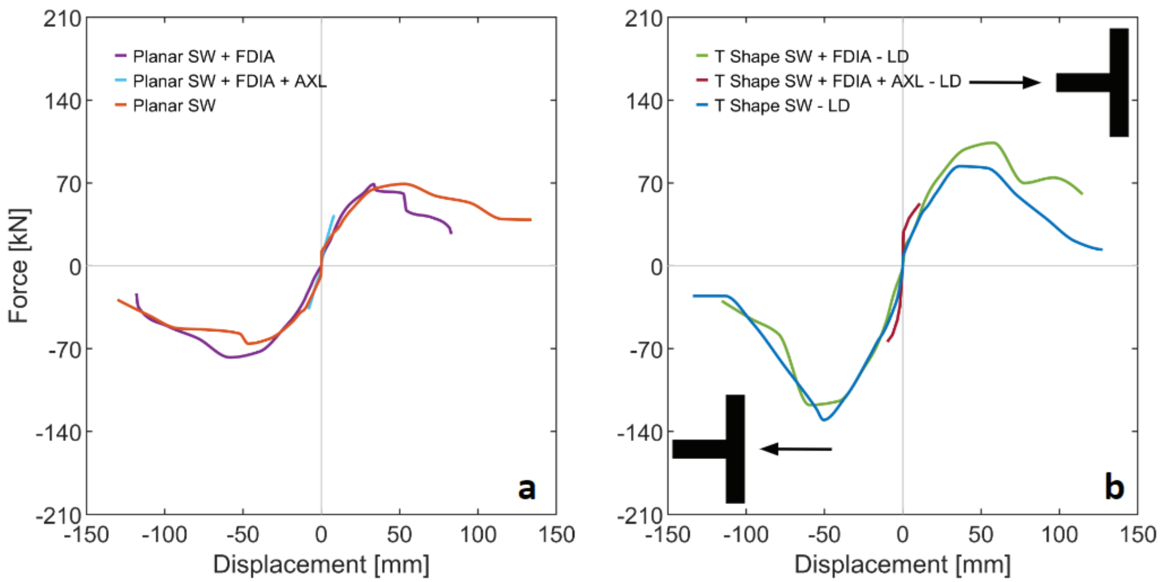

Figure 2. Backbone curves (longitudinal direction) of: (a) a Planar SW; and (b) a T-Shape SW.

The T-shaped SW exhibited lower equivalent viscous damping (ζ_{eq}) than the Planar SW without the diaphragm, despite comparable levels of energy dissipation (Figure 3). However, when FDIA was included, the difference became negligible. Specifically, the T-shaped SW with FDIA exhibited ζ_{eq} values up to 6% higher than those of the Planar SW with FDIA. In the transverse direction, FDIA increased damping by up to 16%. These results highlight the important role of diaphragm stiffness in enhancing damping characteristics in both directions of non-planar SWs.

Secant stiffness decreased with increasing drift, stabilizing between 0.15 and 0.30 kN/mm/m (Figure 3). The T-shaped SW maintained higher stiffness across all drift levels due to the influence of the TSW effect, while FDIA contributed to a more gradual degradation trend. Cumulative energy dissipation was also higher for the T-shaped SW with FDIA, indicating improved energy dissipation as a result of system-level interactions. Overall, FDIA significantly enhanced both stiffness retention and energy dissipation, particularly for non-planar configurations.

The uplift response of the SWs' rocking restraint system showed that the continuous rods remained elastic, with observed hysteresis primarily caused by local crushing and deformation of the wood beneath the bearing plates. The T-shaped SW experienced approximately 35% less maximum uplift compared to the Planar SW, highlighting the contribution of the TSW effect. FDIA further reduced uplift—by up to 25% in the T-shaped SW and up to 50% in the Planar SW. As lateral drift increased, the out-of-plane bending of the diaphragm's collector beam became more significant, helping to redistribute internal forces and limit uplift.

Axial loading (i.e., gravity effects) also contributed to reducing uplift demands. Both SW types exhibited lower tensile stresses in the rod system under the combined FDIA + AXL condition compared to FDIA alone. These findings emphasize the importance of accounting for axial loading when designing anchorage systems and assessing displacement demands in strong wood-frame structures.

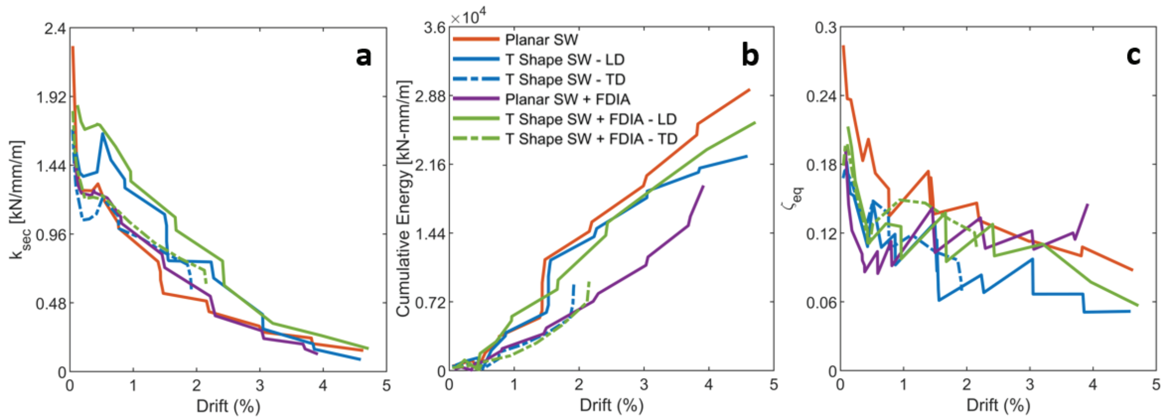

Figure 3. Comparisons between the (a) secant stiffness, (b) cumulative dissipated energy, and (c) equivalent viscous damping of the Planar SW and the T shape SW with different effects.

4 – CONCLUSION

This study shows that it is imperative for practicing engineers to incorporate the TSW, FDIA, and AXL effects into the seismic design of light-frame timber buildings. Such incorporation will mitigate the impact of conservative simplifications that currently result in significant underestimations of the lateral stiffness, leading to underestimated seismic demands and an overestimation of the required stiffness for the overturning restraint systems.

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