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EVALUATION OF THE INFLUENCE OF SYSTEM EFFECTS ON THE LATERAL RESPONSE OF BUILDINGS WITH L- AND U-SHAPED WOOD FRAME SHEAR WALLS THROUGH SHAKE TABLE TESTS

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ABSTRACT: This paper presents part of the findings of a shake table test on a 3-story, 1:2 scale Light Frame Timber Building (LFTB), examining the influence of system effects. Here, system effects refer to a) the effect of transverse walls in non-planar shear wall configurations, b) out-of-plane bending diaphragm interaction with the shear walls, and c) gravity load. The study contributes to comprehending and quantifying system effects, highlighting the benefits of component interaction in LFTBs subjected to lateral loads. Test results demonstrate that system effects significantly reduce story drift demands by increasing the lateral stiffness and damping ratio of the building compared to those of a building in which there are no system effects. For instance, the experimental first-floor secant stiffness was higher than the value predicted by assuming planar shear walls. This underestimation decreases at higher stories, indicating that the gravity load further enhances the benefits of transverse shear walls and out-of-plane bending stiffness interaction. These findings have implications for the design and analysis of LFTBs in seismic regions: their incorporation into seismic design procedures might promote the widespread adoption of LFTBs as a sustainable and resilient construction solution.

KEYWORDS: Timber buildings, system effects, non-planar shear walls, gravity load, out-of-plane bending stiffness.

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1 – INTRODUCTION

The seismic vulnerability of light-frame timber buildings (LFTBs) is a significant concern in earthquake-prone regions. Events such as the 1994 Northridge Earthquake, which caused considerable damage and loss of life in certain LFTBs, highlight the need for a deeper understanding of their seismic behavior [1–4]. In recent years, mid-rise timber buildings (up to 7 stories) have gained traction as a solution to housing shortages, supported by government agencies, academia, and industry—particularly in seismic-risk zones such as Chile. The adoption of off-site construction methods for LFTBs has further strengthened this momentum, offering an alternative to traditional concrete structures.

Currently, however, Chilean design standards restrict LFTBs to four stories. Moreover, residential timber buildings in Chile often feature distinct configurations, notably the "fish-bone" floor plan, which employs non-planar strong wood-frame shear walls and floor/roof diaphragms as part of both the lateral and gravitational load-resisting systems. Despite this, prevailing design methods frequently simplify the analysis by neglecting interactions between structural components, resulting in underestimated global stiffness. This, in turn, necessitates using stronger structural members to satisfy inter-story drift limits. Accordingly, a deeper understanding of the dynamic behavior of LFTBs is needed.

Shake table testing has proven to be an effective method for evaluating the seismic performance of full-scale LFTBs [1,3–5]. While earlier research primarily focused on studying the response of different wall sheathing materials—such as stucco and gypsum finishes—based on North American construction practices [1-4, 6-8], more recent efforts have shifted toward capturing the interaction of structural components within complete buildings [5,9].

One critical aspect of this interaction is known as the "system effect" or "box effect," which accounts for the collaborative contribution of elements like transverse shear walls, diaphragm flexural stiffness, and axial loading. Tomasi et al. (2015) [5] demonstrated the importance of these interactions in both experimental and numerical studies, emphasizing how the response of individual shear walls can be significantly affected by adjacent components.

At the component level, Valdivieso et al. (2024) [10] experimentally investigated non-planar T-shaped shear walls designed to represent ground-level assemblies of a 7-story building designed to Chilean seismic code NCh433 [11]. Their findings revealed that the behavior of non-planar shear walls differs notably from planar walls in terms of stiffness, strength, and deformation capacity—demonstrating the need to consider system effects such as boundary shear wall contributions.

While numerical models have been developed to simulate the seismic response of LFTBs [5,12-14], they often fall short of capturing system effects and complex 3D interactions, such as wall coupling and diaphragm stiffness—particularly in configurations involving non-planar assemblies [10]. This complexity presents modeling challenges that must be addressed to improve seismic performance predictions [8, 10].

This paper underscores the necessity of investigating system effects in LFTBs, drawing on experimental insights from shake table testing. Understanding the interactions between structural components is vital for improving seismic design strategies, especially in earthquake-prone areas.

2 – MATERIALS AND METHODS

The tested specimen is a three-story light-frame timber structure representative of a residential building, designed following the Chilean seismic code NCh433 [11]. Due to the lack of large-scale shake table facilities in Chile, the structure was built at 1:2 scale, resulting in structural elements at half the dimensions of a full-scale building. The footprint of the structure measures 1960 mm by 2760 mm, with each story having a height of 1360 mm. The configuration includes one L-shaped and one U-shaped non-planar shear wall and a planar wall, as shown in Figure 1.

The lateral force-resisting system comprises light-frame timber shear walls and diaphragms in a platform frame configuration. Three wall types (W_1, W_2, and W_3) were used throughout the building height (Figure 1-b). The wall framing uses 41 mm × 138 mm C16 Chilean radiata pine [15] studs spaced at approximately 315 mm on center. OSB sheathing is attached using spiral nails with edge/field spacing ranging from 100/200 mm to 200/400 mm. Overturning resistance is provided by Simpson Strong-Tie hold-downs, including HDQ8-SDS3 and HTT5 models, anchored using recommended screws [16-18].

To ensure effective interaction between transverse shear walls in the non-planar L- and U-shaped configurations, the perpendicular connections between walls were designed to have an x-local axis stiffness of at least 40% of the in-plane stiffness of wall W_1, following recommendations from recent research [19]. To achieve this, four sets of ESCRFTZ 8.0 mm × 300 mm screws were installed at a 45° angle.

Two diaphragm types were used, both with dimensions of 2760 mm × 1960 mm. Diaphragm D_0 is framed with 2×8 C16 radiata pine [15] beams spaced at 300 mm and features enhanced edge and perimeter framing with three to six mechanically joined members. Diaphragm D_1 is framed with 2×6 members spaced similarly. Both diaphragms are sheathed on one side with 15.0 mm plywood, nailed using smooth-shank nails with edge and field spacing of 150 mm and 300 mm, respectively [18].

Testing was conducted on a unidirectional Anco shake table capable of ±1.0 g acceleration, 0.45 m/s velocity,

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and 15 Hz frequency, with a payload limit of 40 kN. To accommodate the full specimen weight, a steel extension table capable of supporting 200 kN was added, though this reduced the effective actuator capacity to 20 kN due to friction losses. Only results from a white noise and harmonic input test under fixed-end conditions are reported here.

Two boundary conditions were tested: isolated and fixed-end. For the isolated test (see [20] for further details), the specimen was placed on four supports connected to the shake table extension, resulting in simple support along the D_0 diaphragm. In the fixed-end setup—reported in this paper—RHS 200 × 150 × 8.5 mm steel beams were installed between the isolator supports to create a continuous edge support, simulating the behavior of strip foundations in real buildings.

Due to the specimen's scale, only selected elements were instrumented, focusing primarily on the first story. The instrumentation included 12 uniaxial accelerometers on each floor, five triaxial wireless accelerometers on the second floor, and six uniaxial wired accelerometers between the second and fourth floors for capturing micro- and strong-motion responses. Seven LVDTs measured diagonal wall drift on the first story, and 15 LVDTs monitored uplift at key wall ends. Additionally, 27 strain gauges were installed in the hold-down anchor bars to capture stress data. Six laser potentiometers recorded absolute building displacement. Nine vertical accelerometers on the first floor monitored out-of-plane diaphragm deformation, providing insight into diaphragm-wall interaction effects.

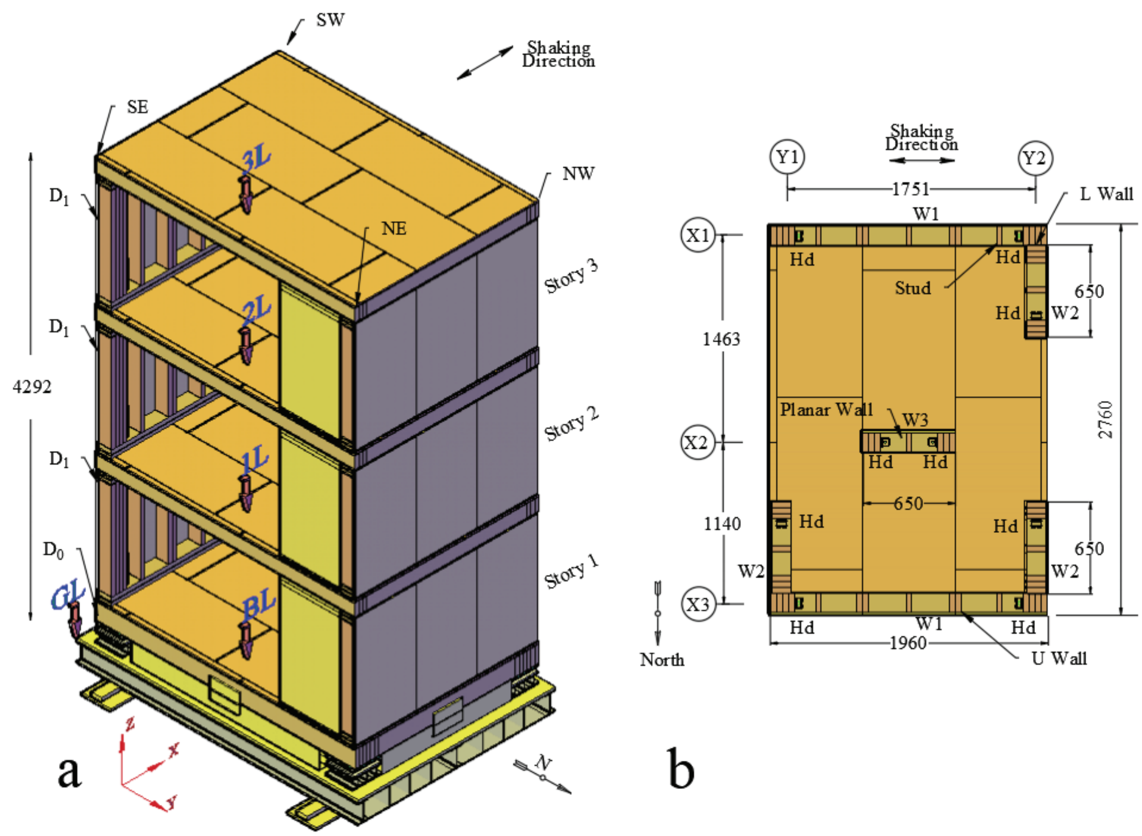

Figure 1. Structure layout: a) 3D view, b) plan view

3 – RESULTS

The dynamic characteristics of the tested specimen were evaluated using a white noise excitation with an amplitude of 0.05 g. System identification, conducted via the ERA-DC algorithm, revealed relatively high damping values across the first three vibration modes. For the fundamental mode, a frequency of 4.16 Hz (T = 0.24 s) and a damping ratio of 7.6% were identified. The second and third modes exhibited even higher damping ratios—17.4% and 16.8%, respectively—with associated frequencies of 8.57 Hz and 12.7 Hz. These damping values significantly exceed the typical 2–5% range generally assumed for timber structures, as reported by Jayamon et al. (2018) [21]. This elevated damping is attributed to system effects—such as three-dimensional interactions between walls and diaphragms—and frictional forces activated at low excitation levels.

Compared with predictions from a numerical model, the identified frequencies were significantly higher, indicating that the tested structure is considerably stiffer than the model suggests. Specifically, the predicted frequencies for the first three modes were 1.36 Hz,

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1.60 Hz, and 2.54 Hz, respectively, each paired with an assumed damping ratio of 2.0%. These discrepancies underscore the importance of accounting for system-level interactions in light-frame timber buildings (LFTBs). The numerical model used for comparison follows state-of-the-art methodologies developed by Pei et al. (2009, 2011) [13,14], which consider only the in-plane contribution of individual shear walls while neglecting interactions with adjacent components, such as diaphragms and transverse shear walls.

Following the dynamic property identification, the specimen was subjected to harmonic excitation with an amplitude of 0.1 g at a frequency of 1.36 Hz—corresponding to the numerically predicted fundamental mode—and a scale factor of 1.0. As shown in Figure 2-a, the peak story drift remained below 0.65%, well under the design drift threshold of 1.3%. The expected design drift was calculated using the Chilean seismic code NCh433 [11], based on a 0.2% design drift multiplied by a response modification factor of R = 6.5. This drift reduction is likely due to frictional damping, three-dimensional coupling effects from the non-planar shear walls, and out-of-plane stiffness contributions of the diaphragms, all of which are especially prominent in fixed-base systems with high inherent damping.

Figure 2-b presents the distribution of peak floor accelerations. A clear whip effect is observed at the third level, where the peak floor acceleration reached 185% of the input acceleration. This response is typical of stiff structural systems and underscores the need to evaluate acceleration demands in high-rigidity buildings.

To further investigate structural behavior, the global hysteretic responses per story and the evolution of secant stiffness across loading cycles were analyzed. Figure 3-a illustrates a notably asymmetric hysteresis response, particularly at the first level, likely due to system effects and the geometric asymmetry of the L-shaped shear wall. Figure 3-b shows progressive secant stiffness degradation across all stories, with the first floor exhibiting the most significant reduction, indicating inelastic behavior during testing.

At a design drift level of 0.2%, the measured strength and stiffness at each story (highlighted in red) were compared to predictions from the SDPWS 2021 analytical model [18] (shown in green), which accounts only for the planar in-plane contributions of wall types W1 and W3 (see Figure 1). The comparison revealed that the actual structural strength was up to 240% greater and the secant stiffness up to 150% greater than those predicted by the model. These substantial differences emphasize the critical impact of system effects in non-planar shear wall configurations and reveal the limitations of simplified modeling approaches that neglect multi-directional interactions.

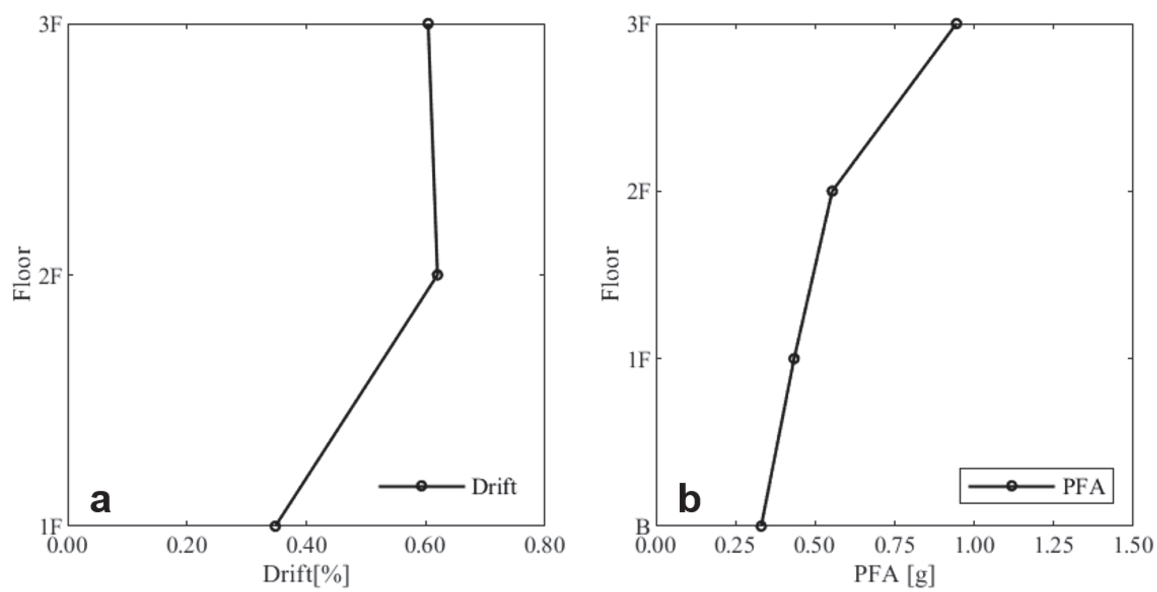

Figure 2. (a) Peak story drift and (b) peak floor acceleration of the structure, subjected to harmonic excitation.

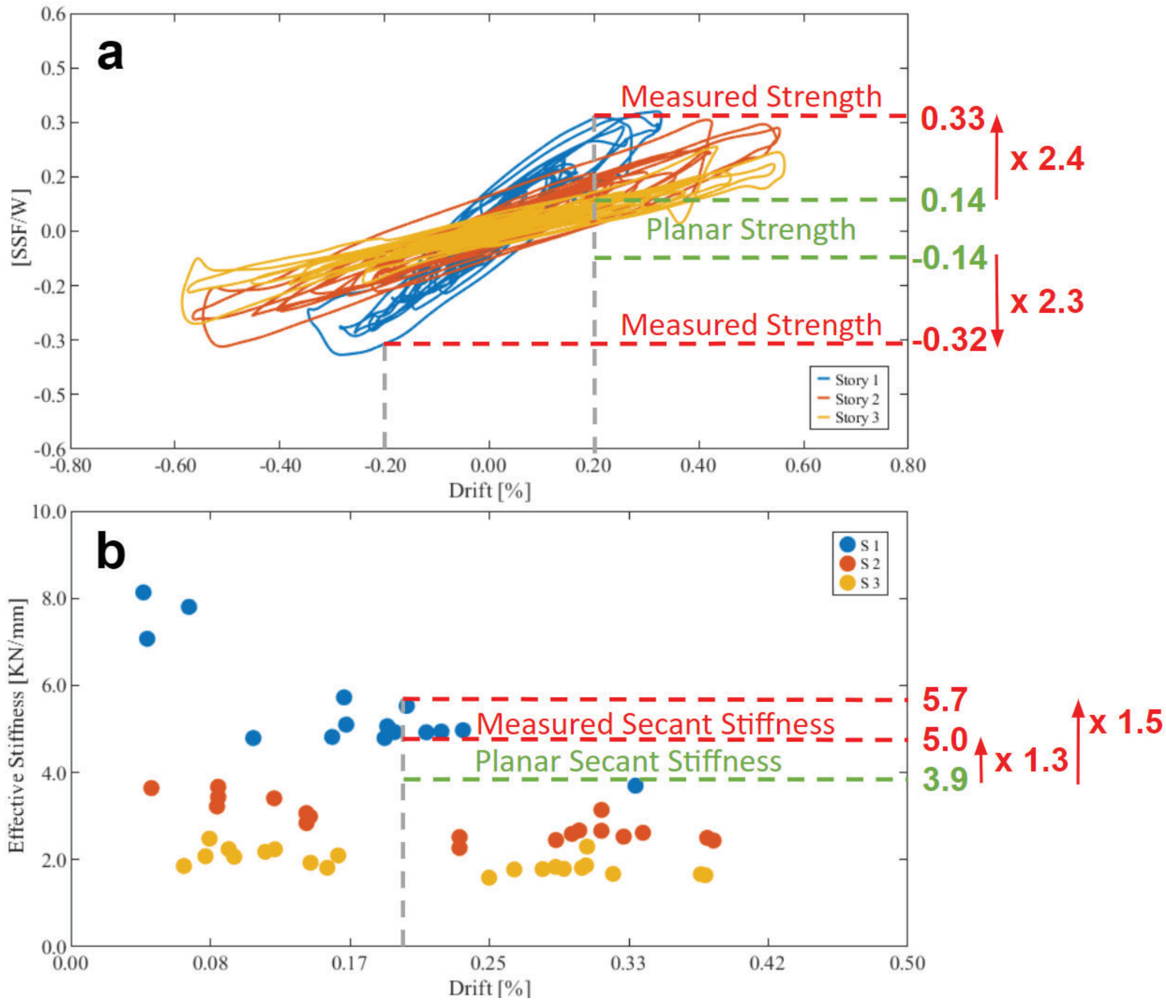

Figure 3. Response to harmonic excitation: (a) hysteretic response of each story; (b) evolution of the shear wall secant stiffness at each story as a function of the lateral drift.

4 – CONCLUSION

This study advances our understanding of system effects in Light Frame Timber Buildings (LFTBs), particularly those with non-planar shear wall configurations, which is a prevalent feature in Chilean construction. Our research sheds light on the substantial benefits of component interaction within LFTBs when subjected to lateral loads, highlighting the critical role of transverse shear walls, shear wall-to-diaphragm interaction, and gravity load. Notably, these system effects have been found to substantially reduce story drift demands, increasing the lateral stiffness and damping ratio of the building. The experimental secant stiffness exceeded predictions based on planar shear wall behavior, with greater benefits observed at lower levels of drift, emphasizing the amplification of transverse shear walls and out-of-plane diaphragm interaction effects by gravity loads. By recognizing and quantifying the positive impact of system effects, it is possible to enhance the safety and performance of LFTBs in high seismic-risk areas.

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