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Seismic evaluation of isolated low-rise thin lightly-reinforced concrete wall building with previous damage: A closed loop dynamic testing approach

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A B S T R A C T

Thin lightly reinforced concrete walls (TLRCW) Buildings are prone to brittle failures due to limited energy dissipation. In LATAM, it is common that these structures have thinner walls than international standards, which makes them cost-effective but vulnerable to the considerable seismic activity in this zone. Hence, unconnected fiber-reinforced elastomeric isolator (U-FREI) devices have been proposed as a low-cost high-deformation capacity solution to enhance the seismic resilience of these structures. Although the U-FREI-based isolation system may reduce the seismic vulnerability of TLRCW buildings as a retrofitting strategy, its passive performance allows to moderate superstructure damage, due to the low deformation capacity and out-of-plane instability of these buildings. This damage may limit the building dynamic response to aftershocks, affecting occupancy and functionality, or even leading to collapse. This study evaluates an isolated, previously damaged low-rise TLRCW building using closed-loop dynamic testing (CLDT). The CLDT, also known as real-time hybrid simulations (RTHS), separates the dynamic system into numerical and experimental substructures. The numerical model represents a six-degree freedom system of the TLRCW building, while the experimental model consists of a TLRCW structural element with induced damage, which replicates a portion of the structure walls. The building performance under four seismic events (El Centro, Kobe, Chihuahua, and Pizarro) with peak accelerations of 0.75•g and 1.25•g was assessed. U-FREI devices reduced maximum drift by over 69.80 % and 54.30 % for damage levels of 10.0 % and 20.0 %, respectively, compared to the fixed-base structure, which reduces the seismic vulnerability post-seismic events.

1. Introduction

1.1. Background of the study

Demographic growth in LATAM countries has exponentially increased the demand for housing in urban areas, strengthening the construction sector. In Colombia, structural engineering has focused on developing efficient technical and economic solutions to address this housing deficit. This challenge has mainly been tackled through the adoption of an industrialized system of housing construction (ISHC) [1]. ISHC uses thin lightly reinforced concrete walls (TLRCW) as the primary structural element of seismic resistance n buildings, facilitating efficient construction using reusable metal formwork. This method facilitates swift and reproducible monolithic casting, leading to reduced labor and material demands [2,3]. Notably, buildings built with this method typically consist of 4–15 levels and employ TLRCW with thicknesses ranging from 8.0 to 15.0 cm. These dimensions fall below the standards prescribed by international norms, thereby categorizing these walls as ultra-thin. These walls integrate welded reinforcements in a single layer, supplemented by additional ductile steel elements matching the

Abbreviations: TLRCW, Thin Lightly-Reinforced Concrete Wall; U-FREI, Unconnected Fiber Reinforced Elastomeric Isolator; CLDT, Closed Loop Dynamic Testing; VTS, Vertical Transfer System; HTS, Horizontal Transfer System; ISHC, Industrialized system of housing construction.; STF, Structural Testing Framework; E-BW, Extended Bouc-Wen.

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thickness of the wall edges, thereby functioning as longitudinal reinforcements [4,5].

While ISHC has demonstrated its efficiency and cost-effectiveness as an alternative for housing construction, subsequent research and reports following earthquakes in Chile (2010), New Zealand (2011), Turkey (2023), have highlighted limitations in the seismic performance of TLRCW buildings. These limitations include reduced ductility, limited energy dissipation capacity, susceptibility to out-of-plane instability, and brittle failure [6–9]. In Colombia, TLRCW buildings demonstrate high slenderness coefficients owing to employing a single layer of electrowelded reinforcement that meets the minimum requirements stipulated in the Colombian seismic-resistant construction regulations (NSR-10 [10–12]). Nevertheless, this reinforcement arrangement elevates susceptibility to out-of-plane instability [13–15], consequently endangering concrete confinement during periods of heightened flexural compression demands at the thin edges of the TLRCW and thus exacerbating construction challenges [16]. Additionally, the utilization of low-ductility reinforcements diminishes the displacement capacity of TLRCW elements [17]. These systems introduce a flexible horizontal interface between the structure and its foundation, effectively absorbing deformation caused by seismic forces and limiting transmission of energy to the superstructure. This concentration of stress in isolator devices reduces the seismic demand on the upper structure, thereby mitigating structural damage, minimizing repair costs, and lowering the risk of functional impairment of the building [18–20].

1.2. Related literature review and research gap

The implementation of traditional isolation devices in developing countries has been limited by the complexity of their manufacturing, structural conditioning requirements, and costs associated with experimental validation of their performance [21]. Consequently, isolation devices without mechanical connections to the structure and the replacement of internal reinforcement with fiber-reinforced materials, known as unconnected fiber-reinforced elastomeric isolators (U-FREI), have been developed. U-FREI devices streamline the manufacturing and installation processes, reducing both weight and cost [22–25]. Pauletta et al. [26], Prakash S. et al. [27] and Banerjee S. et al. [24,28] conducted experimental tests to characterize the dynamic behavior of U-FREI devices. Losanno et al. [29] employed U-FREI to isolate the base of a symmetric 2-DOF steel-concrete structure, which was later replicated by Riascos et al.[30] and Castillo et al. within a hybrid control system. Calabrese et al., [22] utilized U-FREI devices for base isolation to mitigate the seismic vulnerability of unreinforced masonry (URM) buildings, which share the same structural system principle (shear wall) as TLRCW buildings. This illustrates the potential applicability of U-FREI devices to ISHC. In addition, Castillo et al. [17] assessed a TLRCW building structurally healthy with base isolation system and Madera et. al. [31] carried out an exhausted assessment of mechanical properties and associated costs of the U-FREI devices.

Despite the technical advantages of implementing base isolation systems as a retrofitting strategy using U-FREI devices to reduce the seismic vulnerability of TLRCW buildings and enhance the dynamic response of these buildings to seismic loads, its passive performance allows to moderate superstructure damage, due to the low deformation capacity and out-of-plane instability of these buildings [32,33]. These structural damage conditions may restrict the dynamic response of buildings to post-seismic loads or even seismic aftershocks of greater intensity than that of the main event, potentially leading to increased structural damage. Such damage may impose limitations on occupancy or functionality or even result in structural collapse [34–37].

Testing the dynamic response of low-rise TLRCW buildings with pre-existing damage using U-FREI devices as base isolation systems under seismic loads demands substantial technical and economic resources. A pioneering testing approach, termed closed-loop dynamic testing, also known as real time hybrid simulations (RTHS) has emerged as a method to assess the dynamic performance of intricate structural systems or structures with highly nonlinear behavior.[38–40]. In the CLDT, the most pertinent or extensively researched structural elements of the dynamic system, typically demonstrating nonlinear behavior, undergo experimental testing, incorporating inertial effects [41,42]. This testing methodology is well-suited for evaluating devices exhibiting highly nonlinear behavior, such as base isolation systems and TLRCW structural elements, such as those reported by Castillo et. al. [43], Nakata et. al. [44], and Riascos et. al. [30] using U-FREI devices and other studies evaluating reinforce concrete structural elements [45–48], While the remainder of the isolated TLRCW building was analytically assessed with high precision using an analytical model. The experimental and numerical aspects are commonly denoted as experimental and numerical substructures, correspondingly. These substructures create a real-time communication interface using transfer systems to enable their interaction, thereby forming a communication loop to estimate the dynamic response of the system at each time step [49]. The versatility, potential, and precision of CLDTs enable the allocation of resources towards evaluating the experimental components of the system, leading to reduced experimental setup costs, enhanced execution times, and improved performance despite the capacity limitations often encountered in large-scale traditional dynamic experimentation [50,51].

1.3. Objective of the study

This study assesses the seismic performance of a low-rise TLRCW building with pre-existing damage utilizing scaled U-FREI devices for base isolation through the application of the RTHS cyber-physical methodology. These tests were performed to evaluate the reduction in seismic vulnerability of this building type under differences damage scenarios and to validate the utilization of U-FREI devices for base isolation in the industrialized system.

1.4. Research organization

CLDT were performed on the Structural Testing Framework (STF) at Universidad del Valle, Colombia, which served as the transfer system. The remainder of this paper is structured as follows: Section 2 presents a detailed description of the reference structure, including the design and characterization of the pre-damaged TLRCW element and the model U-FREI devices. Section 3 outlines the dynamic sub-structuring of the isolated TLRCW building with pre-existing damage, the transfer system, experimental setup, and applied seismic excitations. Section 4 discusses the results and seismic response analyses of the U-FREI devices, the TLRCW element, and the full structure. Section 5 outlines future research directions. Finally, Section 6 presents the main conclusions of the study.

Table 1
Properties TLRCW building.

Characteristic	*Value*
Location	Cali, Colombia
Building Type	Low-rise TLRCW building
Structural Elements	Reinforced concrete thin walls and flat slabs
Wall Thickness	8.0 cm
Slab Thickness	10.0 cm
Compressive Strength (f′c)	24.5 MPa
Plan Dimensions (x-y plane)	16.50 m × 13.70 m
Story Height	2.50 m
Average Volumetric Wall Density	2.0 % (longitudinal), 2.5 % (transversal)
Gravity Load Distribution	Solid slab of 10.0 cm thickness
Supporting Beams	40.0 cm × 50.0 cm and 40.0 cm × 40.0 cm

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