

Multi-experimental seismic analysis of low-rise thin reinforced concrete wall building with unconnected elastomeric isolators using real-time hybrid simulations

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Abstract

In response to the pressing need for housing and streamlining construction processes, the building industry has embraced innovative construction techniques. One such method, known as the Industrialized Housing Construction (IHC) system, departs from traditional framing systems by utilizing thin-reinforced concrete walls (TRCW). These TRCWs, characterized by high flowability and rapid strength gain, enable quick and efficient monolithic construction of walls and slabs. However, challenges have arisen regarding the structural behavior of these elements, potentially compromising their seismic performance. Given the significant seismic risk, there is a compelling need to develop resilient buildings by using this cost-efficient structural system. This study proposes the use of passive control systems such as base isolation to address this problem. While base isolation has proven effective in other countries, its feasibility in structures using TRCW and its performance during actual seismic events warrants further investigation. This paper presents an innovative approach using Multi-Axial Real-Time Hybrid Simulation (M-RTHS), which combines numerical and experimental components to gain deeper insights into the seismic response of low-rise TRCW buildings with base isolation using unconnected fiber-reinforced elastomeric isolators (U-FREIs). The methodology is detailed and includes the division of the structure into numerical and experimental segments and the use of transfer systems to replicate real seismic excitations, including those from El Centro (USA, 1940), Pizarro (Colombia, 2004), Chihuahua (Mexico, 2013), Loma Prieta (USA, 1989), and Kobe (Japan, 1995), with a maximum amplitude of $7.36 \text{ m} \cdot \text{s}^{-2}$ (0.75 g). The results highlight a remarkable reduction in upper structure floor drifts of over 57.47%, the characterization of the behavior and energy dissipation of each experimental specimen, and the optimal evaluation of M-RTHS. This research paves the way for improving the seismic resistance of buildings in regions prone to seismic activity, especially those using innovative construction methods such as TRCW.

Keywords

base isolation system, thin reinforced concrete walls, multiaxial real-time hybrid simulation, transfer system, dynamic substructuring

Introduction

In recent years, structural engineering has been oriented towards the development of new construction techniques that offer substantial improvements in economic efficiency and expedite certain activities. This is a response to increasing demand for housing, which is directly proportional to demographic growth (Ortega et al., 2021). Several construction systems have been explored, including the industrialized housing construction system (IHCS). IHCS uses thin reinforced concrete walls (TRCW) in a significant portion of the structural area. In addition, it uses highly

fluid concretes to achieve better finishes and is commonly mixed with accelerating additives to obtain the design strength at an early age, allowing monolithic casting of TRCW and slabs for a whole plant per day using reusable

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modular metal formwork. During this phase, this system exhibits significant advantages compared with other construction methods that reduce labor and material requirements, which has generated an important reception in the Latin American construction industry (Kildashti et al., 2021). TRCW buildings typically have a structural wall between 80 and 150 mm in thickness and dimensions below those limited by international standards, which classifies these walls as ultrathin. These types of walls incorporate electrowelded core reinforcements, often arranged in a single layer, which does not create a confined core. The reinforcement quantities are typically 0.25%, complying with the minimum requirements of Colombian regulations on earthquake-resistant construction (NSR-10) (Arteta et al., 2018; Ortega et al., 2023). Depending on the design specifications, the IHCS may require specific types of edge elements composed of longitudinal reinforcement with conventional ductile steel and closed hooks or stirrups to provide confinement to maintain the thickness of the core, which limits its performance under flexural and compressive loading (Arteta et al., 2014; Carrillo et al., 2023).

Several studies have documented that TRCW buildings, after being subjected to seismic events in countries such as Chile (2010), New Zealand (2011), Morocco (2023), and Turkey-Syria (2023), exhibit limited structural performance owing to factors such as low ductility, inadequate energy dissipation capacity, out-of-plane instability, and the occurrence of brittle failures, even when facing wall thickness restrictions were high than 15.0 cm (Abdullah and Wallace, 2018; Cheng et al., 2023; Ibrahim et al., 2024; Massone et al., 2023; Mouhine et al., 2024; Ortega et al., 2023; Wallace et al., 2012). In addition, local slenderness ratios of up to 16.0 have been implemented with a typical height between floors of 2.5 m, which increases vulnerability and out-of-plane instability (Almeida et al., 2017; Carrillo and Alcocer, 2012; Massone et al., 2023). However, the geographical location and geological and seismological conditions of Colombia result in an intermediate to high seismic hazard. Therefore, approximately 87.0% of the population resides in areas with significant seismic risk. Hence, the construction industry has increasingly prioritized the development of robust structures capable of efficiently recovering from exposure to substantial dynamic loads (Segura and Wallace, 2018).

Considering the local seismic risk conditions and structural vulnerabilities observed in TRCW buildings during seismic events, there is a growing need to implement control systems capable of reducing their seismic vulnerability and performance (Galano and Calabrese, 2023). These structural control systems are alternative methods for reducing internal forces in a structure and improving their dynamic properties using passive, active, semi-active, and hybrid control schemes (Castillo et al.,

2024a, 2024b; Dey and Saha, 2019; Peng et al., 2022; Saaed et al., 2015; Spencer Jr and Nagarajaiah, 2003). Base isolation systems have become the most commonly utilized passive structural control systems in buildings owing to their independence from external energy sources and their ability to generate forces in response to structural movements (Calabrese et al., 2019; Losanno et al., 2019, 2020, 2022; Madera Sierra et al., 2019). Traditionally, base isolation systems utilize elastomeric devices reinforced with steel that are capable of withstanding high axial loads while facilitating substantial lateral deformation to concentrate seismic energy dissipation. Nevertheless, their high manufacturing and installation costs present a significant barrier to widespread adoption (Calabrese et al., 2019; Madera Sierra et al., 2019). In order to enhance their cost-effectiveness, traditional connecting plates and steel reinforcements have been replaced with nonconnected elements and fiber reinforcement. These devices are known as unconnected fiber-reinforced elastomeric isolators (U-FREIs). UFREI devices have been utilized as base isolator systems in several studies (Castillo et al., 2024a, 2024b; Losanno et al., 2022; Pauletta, 2019; Riascos et al., 2022), including those involving structural systems similar to those used in low-rise TRCW buildings such as low-rise masonry load-bearing wall buildings (Losanno et al., 2021).

Studies that have focused on assessing the dynamic behavior of low-rise TRCW in base-isolated buildings during possible seismic events have been limited due to technical, spatial, and cost-effectiveness limitations when performing large-scale dynamic tests (Torres et al., 2022). Currently, the most common established methods for experimental testing to evaluate the seismic behavior of structural systems are quasi-static tests, shake table tests, and in the last few years the hybrid simulation tests. Quasistatic tests involve the subjection of structural elements under predefined protocols for loads or displacements to low velocities to avoid inertial effects (Beyer et al., 2008; Calderon et al., 2021; Carrillo and Alcocer, 2013). This limits their application to seismic loads such as those conducted by Ortega et al. (2023), Wallace et al. (2012), Abdullah and Wallace (2018), and Carrillo and Alcocer (2012, 2013), among others (Beyer et al., 2008; Mousavi et al., 2014), to determine the TRCW performance. Shake-Table tests replicate realistic seismic conditions on structural prototypes, which provide feasible and accurate results of structural performance during dynamic loads. However, large-scale tests under this methodology are limited owing to restrictions of size, weight, and applied force under laboratory conditions (Brunesi et al., 2019; Henry et al., 2021; Martinelli and Filippou, 2009; Nagae et al., 2015; Panagiotou et al., 2011). On the other hand, real-time hybrid simulations (RTHS) are a novel experimental technique that divides the dynamic system into two

principal components: numerical and experimental substructures, through a dynamic substructuring methodology (Gao et al., 2014; Nakata et al., 2014; Silva et al., 2018). The structural elements whose behavior can be readily identified are numerically modeled using an analytical model, whereas structural elements with complex or nonlinear behavior are physically constructed and tested under laboratory conditions (Gao et al., 2014; Takanashi et al., 1980). Transfer systems induce boundary conditions and responses of the analytical model to the experimental substructure and acquire feedback states to feedback the numerical substructure, which closes the loop of the dynamic system (Li et al., 2021; Shao et al., 2011; Shao and Griffith, 2013). The RTHS technique offers several advantages over conventional quasi-static or shake table tests, such as significantly reduced experimental costs and requirements of size, time, and applied loads. This methodology concentrates the resources in relevant structural elements evaluated on a large-scale, and the rest of the structure is assessed analytically, which allows for fast, accurate and cost-effective assessments (Castillo et al., 2024a, 2024b; Shao and Griffith, 2013).

Although TRCWs have been widely evaluated in the literature, their seismic performance has traditionally been assessed using quasistatic tests, which do not include the inertial component of seismic events and limit the evaluation to independent structural elements. Likewise, the use of U-FREI devices as base isolation in structural systems with thin load-bearing walls, such as low-rise TRCW buildings, is in its early stages, which requires accurate and reliable experimental validations of their dynamic performance. In an effort to push the boundaries of research in low-rise TRCW buildings and base isolation systems, this study focused on evaluating the dynamic behavior performance of a low-rise TRCW building with U-FREI devices as base isolation using Multi-experimental RTHS (M-RTHS) in order to assess both relevant structural elements in isolated TRCW buildings. These tests were conducted to assess the reduction in the seismic vulnerability of this type of building and validate multi-experimentally the use of U-FREI devices for base isolation in the ISHC and the behavior of a TRCW structural element. Hybrid tests were performed by coupling a unidirectional shake table within the framework of scale model isolator tests and a reaction framework at the University of Valle, Colombia, as transfer systems. The remainder of this paper is organized as follows. Section Main Structure provides the details of the assessed reference structure and a description of the experimental structural elements. In Section Real-Time Hybrid Simulation, the dynamic substructuring of the isolated low-rise TRCW building with U-FREI devices, transfer systems employed, experimental setup, and seismic excitations are described. A detailed analysis of the seismic performance of the

U-FREI devices and low-rise TRCW building with U-FREI devices as base isolators is presented in Section Results. In this section, the performance of RTHS is evaluated. Finally, Section 5 presents the conclusions of the study.

Main structure

Reference structure

The reference structure represents a typical low-rise TRCW building, which is located in Cali, Colombia and was initially used by (Castillo et al., 2024a, 2024b). The selected structure was designed based on the IHC system using TRCWs with thicknesses ranging from 80–100 mm and interfloor slabs. Normal-weight concrete with a compressive strength of $f'_c = 24.5 \text{ Mpa}$ was considered for all the structural elements. In addition, the average volumetric wall density was established as 2.0% and 2.5% in the longitudinal and transverse directions, respectively. TRCW building has five floors with inter-story heights of 2.5 m and plan dimensions of 16.5 m and 13.7 m in the x - y directions, respectively, as presented in Figure 1 (left-top). Moreover, a 100.0 mm thick solid slab with red-colored 400×500 mm and orange-colored 400×400 mm beams was used to obtain a uniform load distribution at the base. These beams work as the foundation for TRCWs, transmitting the load to the 12.0 U-FREI devices, as shown in Figure 1 (top-right and bottom). The beam elements were considered with a compressive strength of $f'_c = 24.5 \text{ Mpa}$.

The low-rise TRCW building with U-FREI devices as the base isolation system was modeled using the finite element software ETABS19. Shell-membrane elements were used for the slabs, thin shell elements for the walls, and frame elements for the beams. The slabs at all the levels were assumed to behave as rigid diaphragms. The conventional condition of a structural damping ratio $\zeta = 5.0\%$ was considered. The frequencies in the x - y directions for the first two modes were 4.46 Hz and 4.77 Hz, respectively. In contrast, for the isolated condition, a target period of 1.90 s was achieved, resulting in rigid-body behavior in the superstructure supported by the isolation system. The structural damping ratio was not considered for the isolated building, considering only the damping provided by the hysteresis behavior of the U-FREI devices (Castillo et al., 2024a, 2024b).

Thin reinforced concrete wall (TRCW)

The first experimental substructure corresponds to a TRCW element denoted as M3R10, as shown in Figure 2. The TRCW specimen was constructed using concrete with a compressive strength of $f'_c = 24.5 \text{ Mpa}$. The

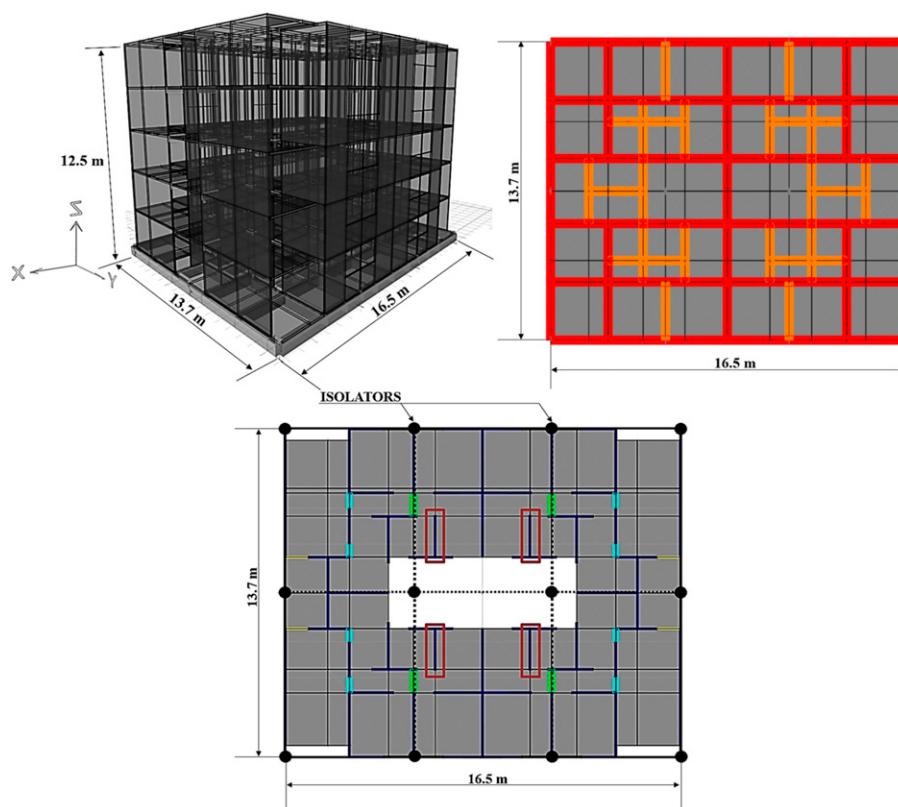


Figure 1. Reference structure. Structural isometry (top-left), beam frame of the isolation system (top-right), and structural plan with U-FREI devices (bottom).

configuration and geometry of the TRCW-M3R10 specimen are listed in Table 1.

The reinforcement of the TRCW-M3R10 structural specimen was thoroughly detailed and is listed in Table 2. In addition, the geometric properties and materials used were indicated.

Base isolation system: U-FREI devices

Two small-scale U-FREI specimens were used as the second experimental substructures. U-FREIS devices were built with local manufacturing and have been used in previous studies (Castillo et al., 2024a, 2024b; Riascos et al., 2022). These isolators are composed of 15.0 layers of 2.0 mm thick rubber, reinforced with 14.0 layers of 1.0 mm thick polyester fiber, as shown in Figure 3.

Real time hybrid simulation (RTHS)

In recent years, innovative methodologies have implemented to evaluate the dynamic behavior of structural systems, Real-Time Hybrid Simulations (RTHS) are a notable experimental technique of example (Castillo et al., 2024a, 2024b; Li et al., 2021; Nakata et al., 2014; Shao and Griffith, 2013). The RTHS technique retains the concept of

dynamic substructuring used in traditional hybrid simulations, which allows division of the dynamic system into experimental and numerical substructures. These substructures are connected by transfer systems to induce boundary conditions and measure the state of the dynamic system (Takanashi et al., 1975, 1980). In addition, RTHS involves real-time execution, which allows the inclusion of inertial conditions in the experimentally tested specimens (Darby et al., 1999; Silva et al., 2020).

In this study, the RTHS technique was employed to evaluate the seismic performance of a low-rise TRCW building with base isolation under reference seismic events, using continuous feedback at a rate frequency of 1024 Hz. The testing and homologation framework (THF) and small-scale isolator framework (SS-IF) of the University of Valle, Cali-Colombia, were used as transfer mechanism systems, which had robust and accurate control systems type H_∞ . This robust control incorporate a time delay compensation in its algorithms.

Numerical substructure (NS)

An analytical model of 6.0 condensed translational degrees-of-freedom (DOF) as shear frame was proposed to model the Y-axis behavior of the isolated low-rise TRCW

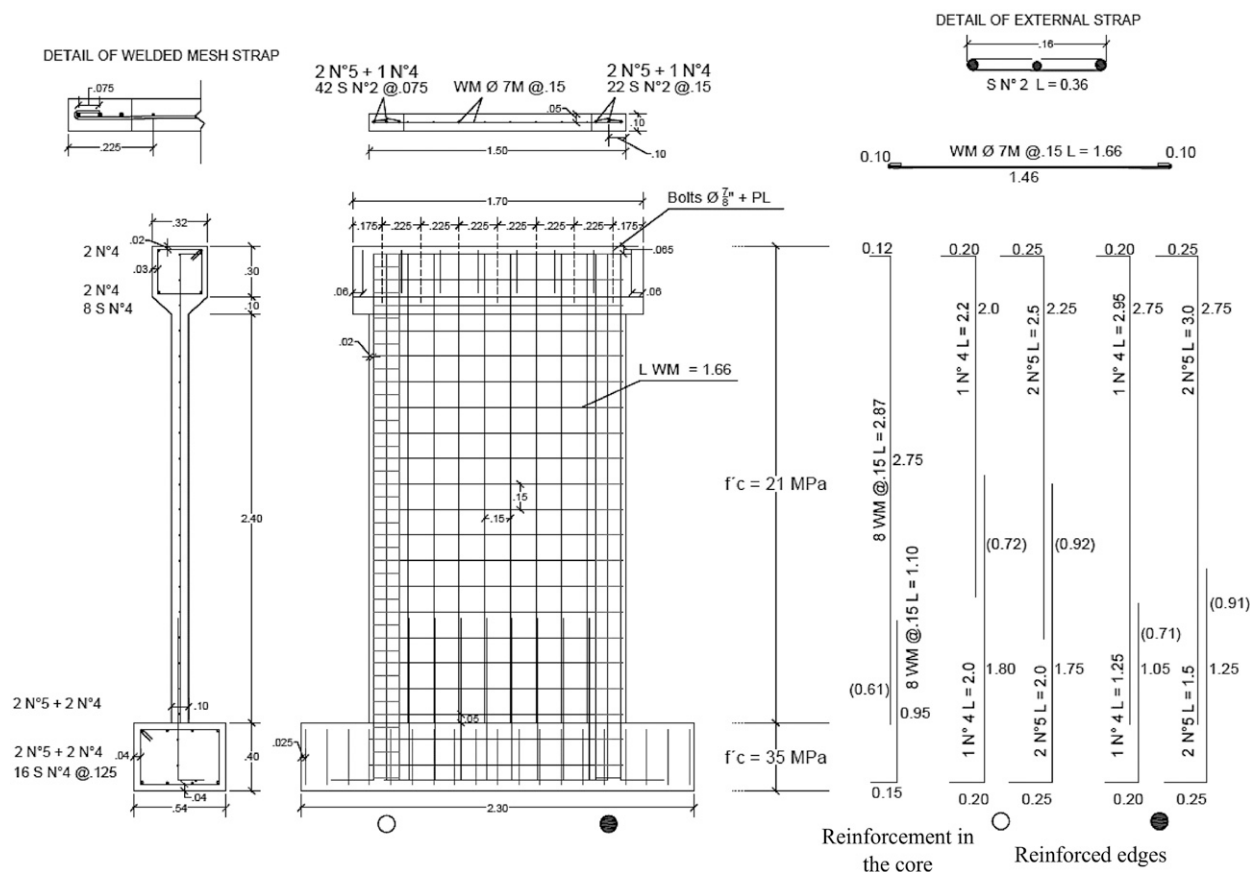


Figure 2. Specification of the TRCW-M3R10 specimen.

Table 1. Properties and general geometry of TRCW-M3R10.

Item	Traversal section	t_w (mm)	l_w (mm)	h_w (mm)	f'_c (MPa)	Reinforcement in the core of the wall (mm)	ρ_{β} west (%)	ρ_{β} east (%)	Axial load factor $[L_N/(f'_c \cdot A_g)]$
M3R10	Rectangular	100	1500	2400	24.5	Welded Mesh $\varnothing$ 7.0 mm every 150		2.62	4.80%

Table 2. Reinforcement and materials of the TRCW-M3R10 specimen.

Item	Element	Base (m)	Height (m)	Length (m)	f'_c (MPa)	Longitudinal reinforcement	Transversal reinforcement (cm)
M3R10	Upper beam	0.32	0.30	1.70	24.5	4 N°4	8 stirrup N°4 @ 22.50
	Lower beam	0.54	0.40	2.30		4 N°5 + 4N°4	16 stirrup N°4 @ 12.50
	Border element [West]	0.1	2.40	0.20		2 N°5 + 1N°4	42 stirrup N°2 @ 7.50
	Border element [East]	0.1	2.40	0.20		2 N°5 + 1N°4	22 stirrup N°2 @ 15.0
	Wall	0.1	2.40	1.50		Welded Mesh $\varnothing$ 7.0 mm @ 15.0 cm	

building, as shown in Figure 4. This is based on the premise that the U-FREI devices can maintain the elastic range of the TRCW structure. The analytical model constituted a numerical substructure (NS). The dynamic responses of this analytical model were adjusted to the response obtained in the

model developed using ETABS software, according to the methodology proposed by (Castillo et al., 2024a, 2024b), which consists of inducing a sweep with constant amplitude and range frequencies between 0.1 and 20 Hz. The shear frame dynamic properties adjusted are listed in Table 3.

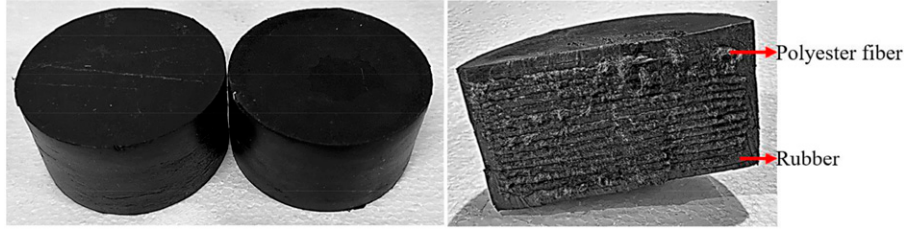


Figure 3. Small-scale U-FREI specimens.

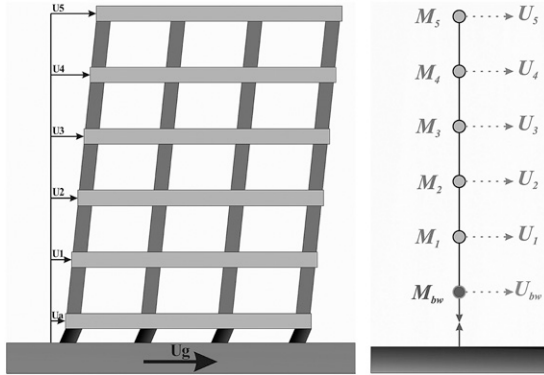


Figure 4. Numerical model of the isolated low-rise TRCW building. model DOF (left) and masses and stiffnesses per floor (right).

Table 3. Dynamic properties of the isolated low-rise TRCW building.

Floor level	Masa M_i [ton]	Stiffness M_i [$kN \cdot m^{-1}$]	Damping C_i [$kN \cdot s \cdot m^{-1}$]
Isolated Base	171.91	BW*	BW*
No. 1	159.83	3091.80*1e3	3549.80*1e3
No. 2	159.88	1787.00*1e3	2186.70*1e3
No. 3	159.88	1197.72*1e3	1571.00*1e3
No. 4	159.88	845.42*1e3	1202.90*1e3
No. 5	138.83	470.45*1e3	769.02*1e3

*BW $\rightarrow$ Extended Bouc – Wen model.

The dynamic behavior of the structure is governed by Eq. (1), where M_r , C_r , and K_r are the mass, damping, and stiffness matrices, respectively, identified for the simplified 6-DOF model. $\ddot{x}$, $\dot{x}$, and x are the relative acceleration, velocity, and displacement vectors, respectively. By applying dynamic sub-structuring, the response of the isolation system was extracted from the model of the isolated low-rise TRCW building to be included as a feedback force using the extended Bouc-Wen numerical model, whose properties are presented in Table 4, which were validated by (Castillo et al.,

2024a, 2024b), and the force measured experimentally for the U-FREI devices. In addition, the same methodology was applied to extract the dynamic properties of the TRCW structural element from the low-rise TRCW building analytical model, and this force was measured experimentally for the entire dynamic system. This analytical approach allows feedback between the analytical model of the isolated low-rise TRCW building with the experimentally measured force from the TRCW structural element (F_{TRCW}) and U-FREI devices as an isolation system (F_{ISO}), as presented in equation (2).

$$M_r\{\ddot{x}\} + C_r\{\dot{x}\} + K_r\{x\} = -M_r\Gamma_g a_g \quad (1)$$

$$M_n\{\ddot{x}\} + C_n\{\dot{x}\} + K_n\{x\} = -M_r\Gamma_g a_g - \Gamma_{ISO}F_{ISO} - \Gamma_{TRCW}F_{TRCW} \quad (2)$$

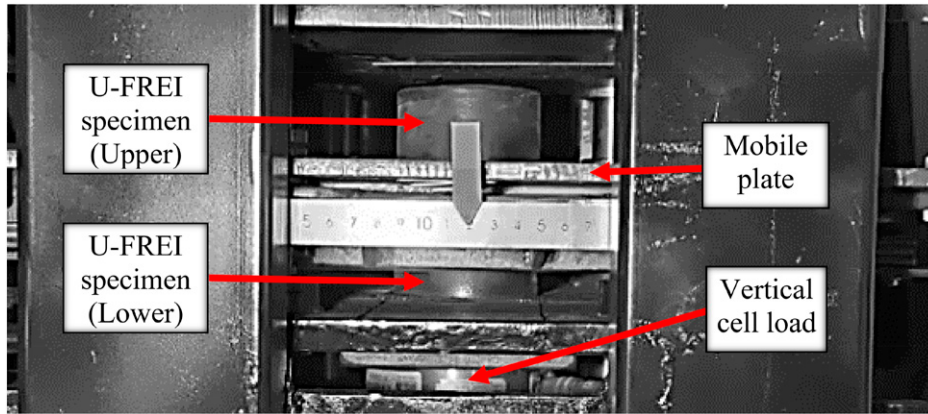
$$\begin{Bmatrix} \dot{x} \\ \ddot{x} \end{Bmatrix}_{[12 \times 1]} = \begin{bmatrix} 0 & I \\ -M_n^{-1}K_n & -M_n^{-1}C_n \end{bmatrix}_{[12 \times 12]} \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix}_{[12 \times 1]} + \begin{bmatrix} 0 & 0 & 0 \\ -\Gamma_g & -M_n^{-1}\Gamma_{TRCW} & -M_n^{-1}\Gamma_{ISO} \end{bmatrix}_{[12 \times 18]} \times \begin{Bmatrix} a_g \\ F_{TRCW} \\ F_{ISO} \end{Bmatrix}_{[18 \times 1]} \quad (3)$$

$$\begin{Bmatrix} U \end{Bmatrix}_{[6 \times 1]} = \begin{bmatrix} 0 & I \end{bmatrix}_{[6 \times 12]} \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix}_{[12 \times 1]} + \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}_{[6 \times 18]} \begin{Bmatrix} a_g \\ F_{TRCW} \\ F_{ISO} \end{Bmatrix}_{[18 \times 1]} \quad (4)$$

The first restorative force of the system is resulting from the experimentally acquired force from the TRCW structural element, are determined by the term $\Gamma_{TRCW} \cdot F_{TRCW}$, where the influence vector $\Gamma_{TRCW} = [1 \ -1 \ 0 \ \dots \ 0]^T$ indicates the degrees of freedom (DOFs) to which the force is

Table 4. Extended Bouc-Wen model constant increased for the isolation system.

$b \text{ [kN} \cdot \text{m}^{-1}]$	$Ca \text{ [kN} \cdot \text{s} \cdot \text{m}^{-1}]$	$S_1 \text{ [kN} \cdot \text{m}^{-1}]$	$S_3 \text{ [kN} \cdot \text{m}^{-3}]$	$S_5 \text{ [kN} \cdot \text{m}^{-3}]$	A	γ	β	γ	η
457.00	0.936	99.84	-4.211×10^4	9.567×10^6	1.00	0.375	613.40	488.30	1.00

**Figure 5.** The experimental assembly of the TRCW-M3R10 specimen on the THF.**Figure 6.** The experimental assembly of U-FREI devices in the SS-IF.

applied. Similarly, a_g represents the ground acceleration, and the vector $\Gamma_g = [1 \ 1 \ 1 \ \dots \ 1]^T$ specifies the incidence of the seismic excitation on the DOFs. Finally, the term $\Gamma_{ISO} \cdot F_{ISO}$, indicates the force from the numerical isolation model and experimentally acquired force from U-FREI devices, and $\Gamma_{ISO} = [1 \ 0 \ 0 \ \dots \ 0]^T$ represents the incident DOF. Based on this formulation, the state-space representation is formulated, as shown in equations (3) and (4), for three inputs to the system and six output DOFs.

Experimental substructure (ES)

The experimental substructure (ES) was initially composed of a full-scale TRCW experimental specimen, denoted as TRCW-M3R10, which represents four structural elements similar to the reference structure described in Section 2. The four structural elements selected, highlighted in Figure 1 (bottom), represent approximately 12.0% of the lateral force capacity of the low-rise TRCW building evaluated. The experimental assembly of the TRCW-M3R10 specimen in

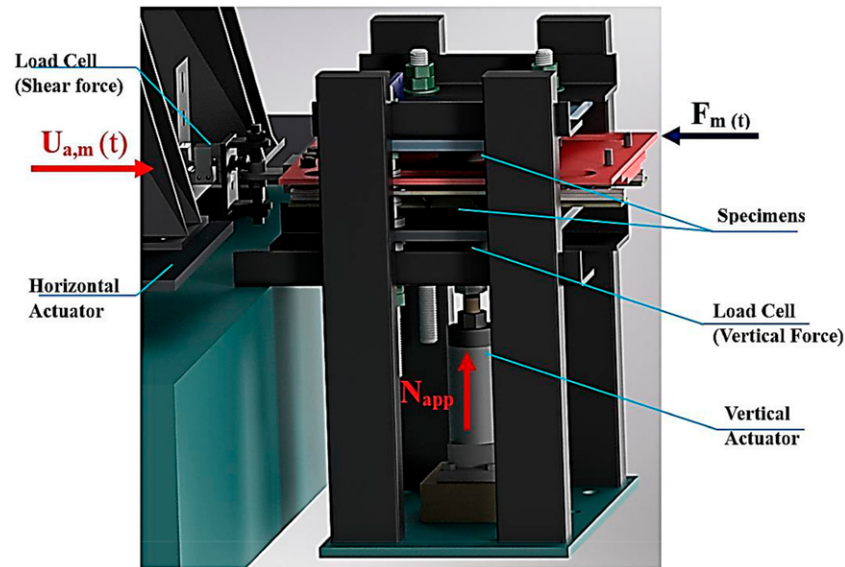


Figure 7. Setup of the small-scale isolator Framework (SS-IF).

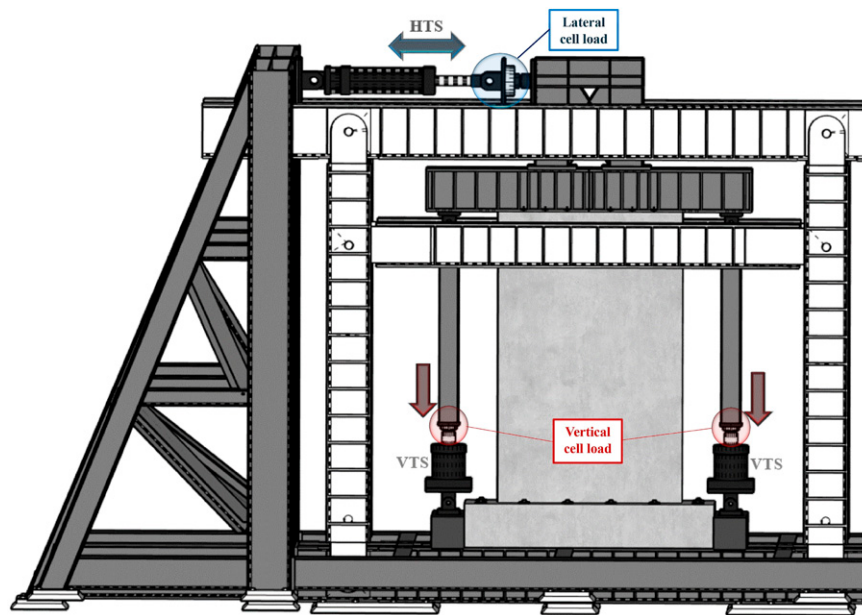


Figure 8. Setup of the testing and homologation framework (THF).

THF is shown in Figure 5, which highlights the essential components of the mechanism for the development of axial and lateral loads.

Likewise, the dynamic behavior of two isolation devices was substructured from the isolated reference structure, represented as shear frame, and feedback of the result load generated by two reduced-scale experimental U-FREI devices using scale factor of stiffness and form, according to similarity laws. These specimens were evaluated in the SS-IF, as described in Section 2 and shown in Figure 6.

Transfer systems

In the RTHS technique, the transfer systems replay the behavior of the NS and induce it to the ES, which generates boundary conditions. This transfer of states between substructures requires high accuracy in the response of mechanical devices.

Small-scale isolator framework (SS-IF). The small-scale isolator framework (SS-IF), used as a transfer system in other studies (Castillo et al., 2024a, 2024b; Riascos et al., 2022),

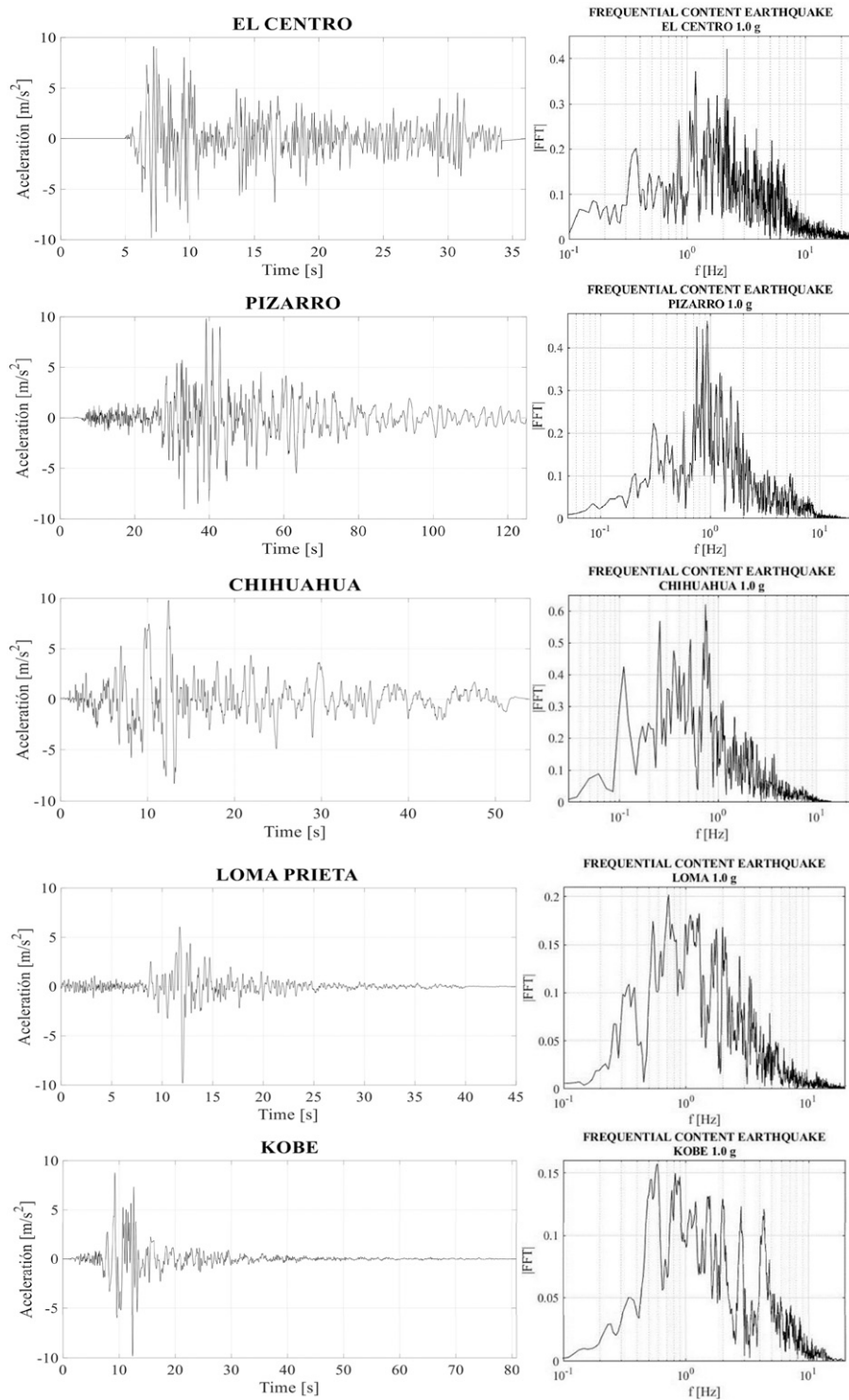


Figure 9. Seismic events evaluated.

serves the purpose of housing the two scaled U-FREI devices and applies a vertical load (N_{app}) using an actuator controlled by a servo valve. This hydraulic system continuously fed the vertical transfer system to load the experimental specimens axially at 19.0 kN. The isolated low-rise

TRCW building has a variation in the vertical load of the isolators of less than 10.0% during seismic excitations, which allows consider the vertical load on U-FREI devices as constant. U-FREI devices were separated by a steel movable plate, which received horizontal displacement

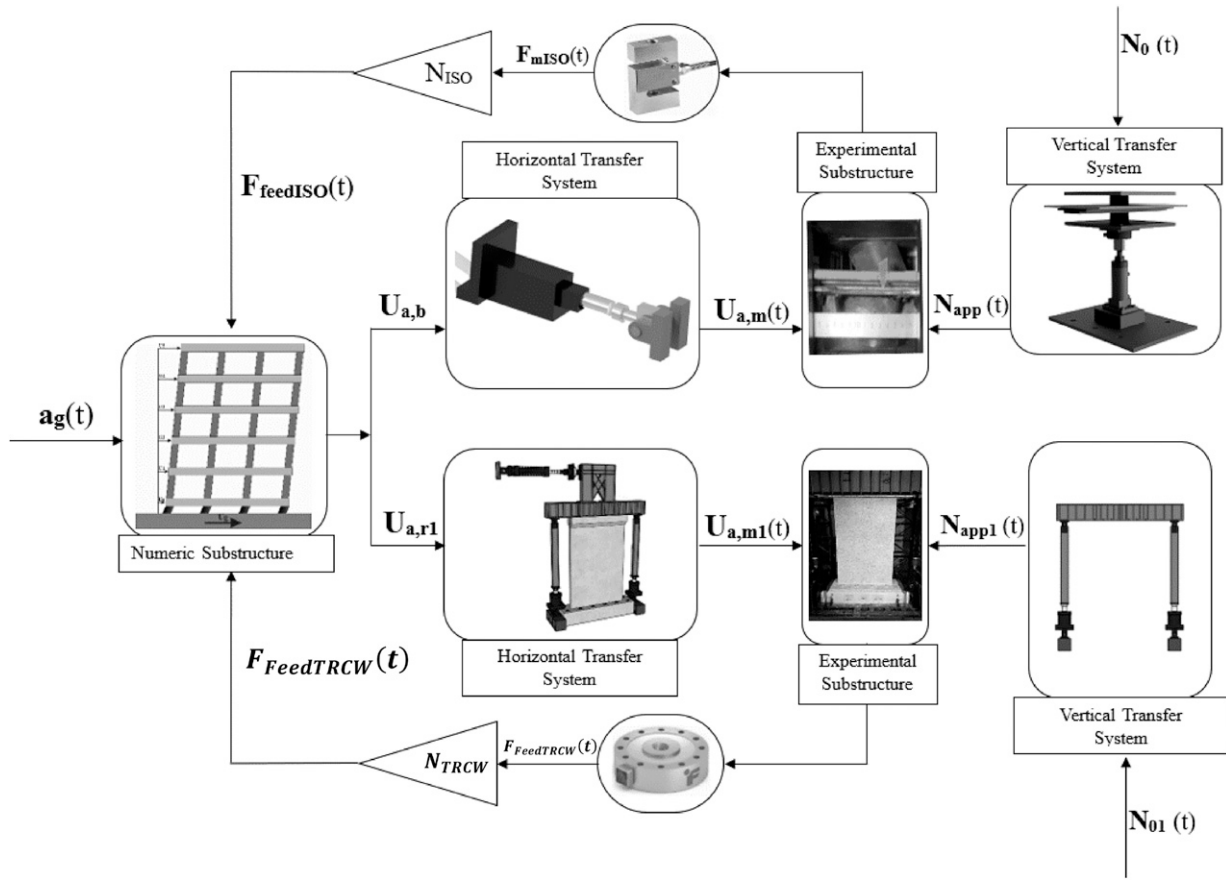


Figure 10. Experimental multi-axial dynamic loop RTHS scheme.

($U_{a,m}$) transmitted by a horizontal actuator and generated a resulting load (F_m) product of the friction load of the U-FREI devices due to their unconnected condition, as shown in Figure 7.

The displacement, corresponding to the response of the reference structure, was scaled using form and stiffness factors and induced by SS-IF to maintain the similarity of scale in the analysis. In addition, robust control type H_∞ in the hydraulic cylinder was integrated to faithfully reproduce the boundary conditions. The F_m load was transmitted in real-time to the NS to close the dynamic system.

Testing and homologation framework (THF). The Testing and homologation framework is designed to perform tests on full-scale structural specimens subjected to lateral loads, as shown in Figure 8. Simultaneously, THF was used as the horizontal transfer system (HTS) and vertical transfer system (VTS) to evaluate the structural specimen TRCW-M3R10, as used in quasistatic studies (Ortega et al., 2023). This prototype consists of a metal frame with braced columns and beams attached laterally to a reaction wall, which allows vertical deformation in TRCW-M3R10 and, independently, a lateral displacement. In addition, the THF

integrates a multiaxial acquired system composed of vertical and lateral cell loads, which allows feedback of the NS with the experimental response of the structural specimen generated by states of the isolated low-rise TRCW building. In this study, robust control type H_∞ in a horizontal hydraulic cylinder was integrated to faithfully reproduce the boundary conditions. The load measured by the lateral cell load was transmitted in real-time to the NS to close the dynamic system.

Seismic events

The seismic behavior performance of the isolated low-rise TRCW building was assessed using multiple Real-Time Hybrid Simulations (M-RTHS), which were performed using the following international reference source seismics: El Centro (USA, 1940), Pizarro (Colombia 2004), Chihuahua (Mexico 2013), Loma Prieta (USA 1989), and Kobe (Japan 1995). All seismic events were scaled to a maximum amplitude of $7.36 \text{ m} \cdot \text{s}^{-2}$ (0.75 g). The time and frequency response for each evaluated seismic event, with a maximum amplitude of $9.81 \text{ m} \cdot \text{s}^{-2}$ (1.0 g), is shown in Figure 9.

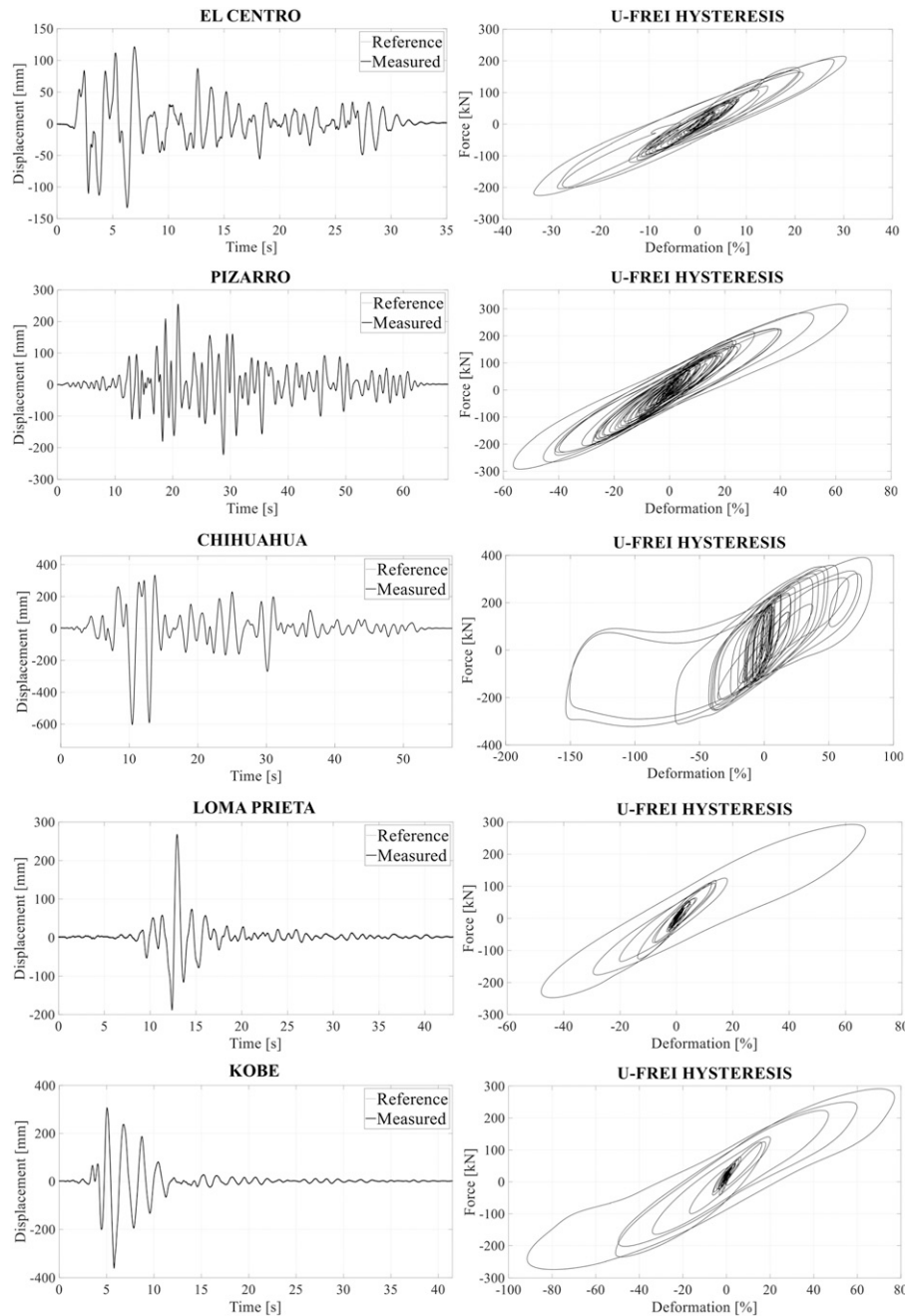


Figure 11. Experimental hysteresis of the U-FREI devices as base isolation system of the low-rise TRCW building.

Experimental setup

The evaluation of a reference structure using RTHS techniques involves interconnecting numerical substructures (NS), experimental substructures (ES), and transfer systems (TS) through a dynamic loop developed in real-time. In this study, the isolated low-rise TRCW building was evaluated dynamically at the base of the NS using seismic inputs, which produced a displacement response

$U_{a,b}$ corresponding to the reference signal of the SS-IF. This framework induces a displacement $U_{a,m}$ on scaled U-FREI devices, which is the first ES. Simultaneously, a constant axial load (N_{app}) of 19.0 kN was sustained on the experimental isolators to replicate the boundary conditions between the base isolation system and superstructure of the building. The experimental response of the U-FREI devices (F_{mISO}) was acquired by a

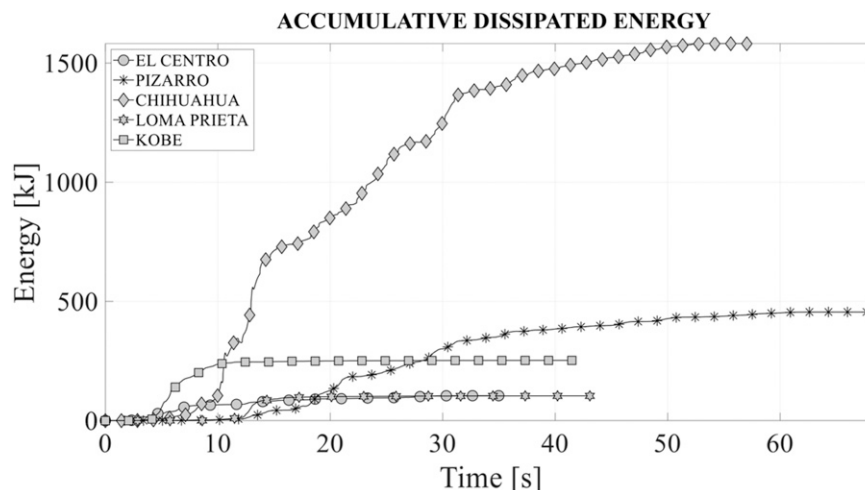


Figure 12. Accumulative dissipated energy of the U-FREI devices.

horizontal cell load and processed by the number of seismic isolators located at the base of the structure, which composed the feedback force $F_{feedISO}$ to feedback the NS, completing the first experimental dynamic loop. In contrast, NS generates a displacement $U_{a,r1}$ at the first level, which constitutes the reference signal of THF. This framework induces a displacement $U_{a,m1}$ on the TRCW-M3R10 specimen, the second ES, using HTS. Simultaneously, the VTS induced on the structural specimen an axial load (N_{appl}) of 19.5 tons to simulate the interface conditions of the TRCW specimen at the level of the reference structure. Likewise, the experimental response of the TRCW-M3R10 prototype (F_{mTRCW}) was acquired by a horizontal cell load and processed by the number of structural specimens located at the first level of the structure, which comprised the feedback force $F_{feedTRCW}$ to feedback the NS, completing the second experimental dynamic loop, as shown in Figure 10. In addition, all the feedback dynamic loops were developed using a sampling frequency of 1024 Hz and transfer systems using robust control type H_∞ to improve the accuracy of RTHS tests.

Results

Seismic performance of the base isolation system: U-FREI devices

The experimental dynamic response of the U-FREI devices as a base isolation system for the reference low-rise TRCW building, experimentally obtained using the RTHS technique, was evaluated under five international reference seismic events. The experimental hysteretic behavior of the specimens was calculated, which contained a characteristically viscoelastic behavior and an important energy

dissipation capacity according to their desired performance, as shown in Figure 11.

The accumulative energy dissipation (AED) of the U-FREI devices for all seismic events is shown in Figure 12. The AED developed by isolation specimens during the Chihuahua event was $\approx 300\%$ higher than that of the other seismic events, mainly attributed to a resonance phenomenon between the base isolation system and the frequency content of this seismic event.

Seismic performance of the structural specimen: TRCW-M3R10

The structural dynamic response of the full-scale TRCW-M3R10 specimen as a component of the first level of the reference low-rise TRCW building, experimentally obtained using the RTHS technique, was evaluated under five international reference seismic events. The experimental hysteretic behavior of the structural specimen was determined, which developed linear behaviors owing to the control action performed by the base isolation system. In addition, a low energy-dissipation capacity was identified, as shown in Figure 13.

The AED of the TRCW-M3R10 specimen for all seismic events is shown in Figure 14. The Chihuahua and Pizarro earthquakes were seismic events with higher affectation to the isolated low-rise TRCW building, which reached an AED higher than 200% compared to other seismic events, as shown in Figure 14. However, in all cases, the performance of the base isolation system using U-FREI devices decreased the seismic vulnerability of the reference low-rise TRCW building, which maintained a maximum drift of less than 0.05% in the structural element. This drift level has been recommended in recent

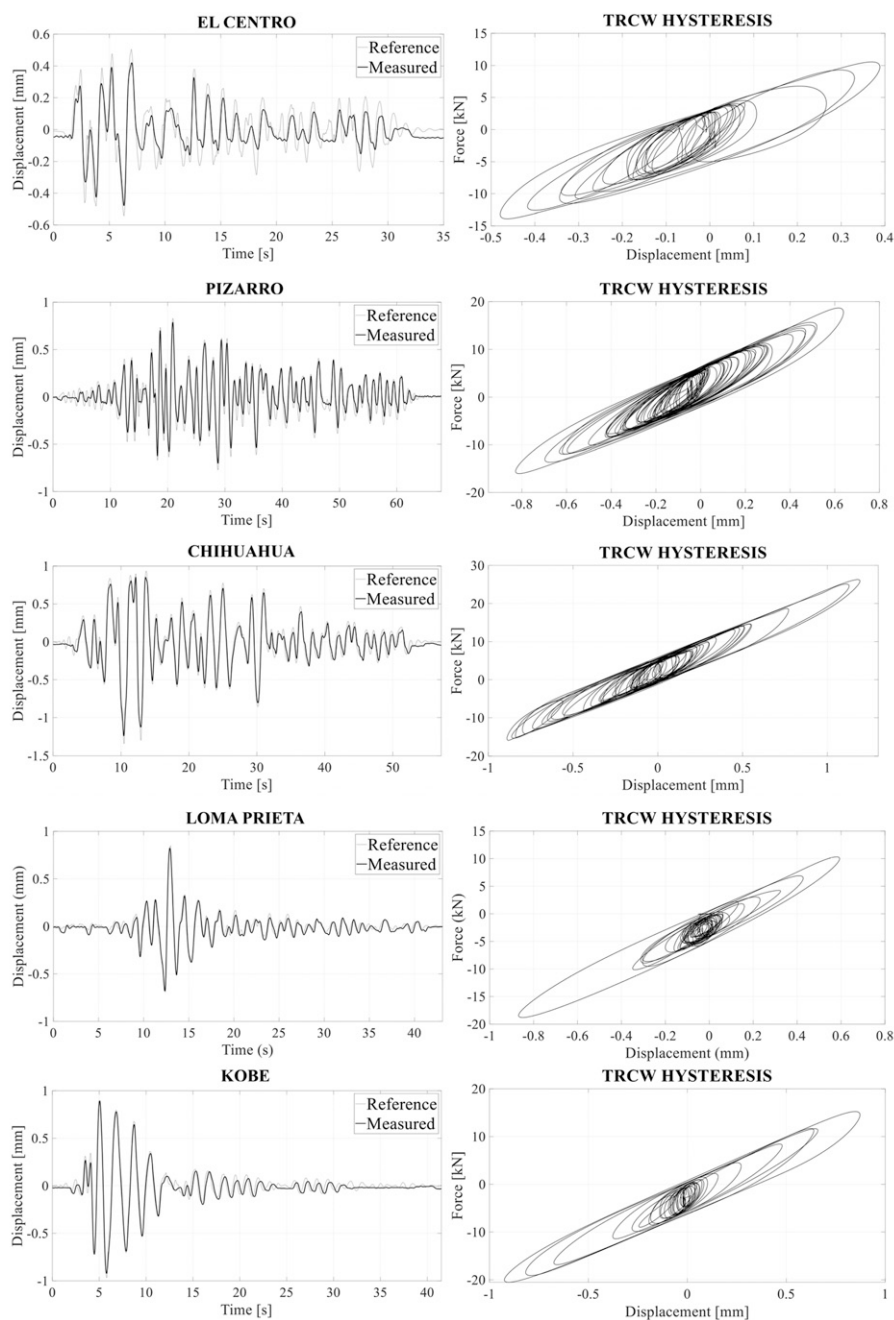


Figure 13. Experimental hysteresis of the TRCW-M3R10 specimen as component in the first level of the low-rise TRCW building.

studies to protect the dynamic performance of this structural system (Arteta et al., 2018).

Low-rise TRCW building seismic performance with U-FREI devices as a base isolation system

The dynamic behavior performance of the low-rise TRCW building was assessed using U-FREI devices as a seismic isolation system through RTHS techniques and a

fixed base using a numerical model. Each evaluation was subjected to the seismic events described in Section 3. The relative displacements or interstory drifts generated in each case were evaluated for the structural system, as listed in Table 5. The U-FREI devices, used as isolation systems, generated a reduction in the maximum building drift of 83.98%, 75.18%, 57.47%, 76.77% and 83.45% for The Centro, Pizarro, Chihuahua, Loma Prieta, and Kobe earthquakes, respectively, compared to the non-isolated structure, as shown in Figure 15. These results

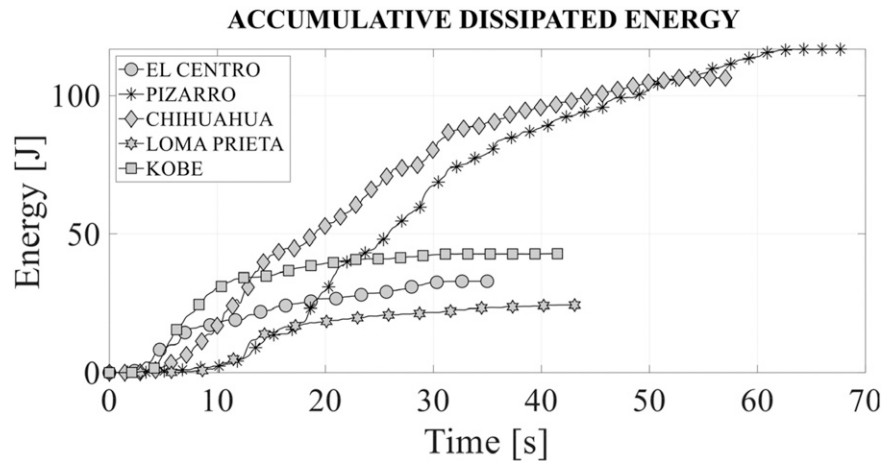


Figure 14. Accumulative dissipated energy of the TRCW-M3R10 specimen.

Table 5. Inter-story drifts generated in each case evaluated of the reference RCWT building.

Item	Seismic events	Story 1 (%)	Story 2 (%)	Story 3 (%)	Story 4 (%)	Story 5 (%)
Isolated	El Centro	0.0216	0.0305	0.0342	0.0323	0.0276
	Pizarro	0.0330	0.0458	0.0505	0.0465	0.0387
	Chihuahua	0.0537	0.0749	0.0832	0.0771	0.0649
	Loma Prieta	0.0335	0.0462	0.0506	0.0460	0.0380
	Kobe	0.0387	0.0544	0.0611	0.0575	0.0490
Fixed-base	El Centro	0.1115	0.1669	0.2055	0.2311	0.2331
	Pizarro	0.1139	0.1705	0.2056	0.2052	0.1841
	Chihuahua	0.1054	0.1593	0.1956	0.2021	0.1910
	Loma Prieta	0.1235	0.1838	0.2199	0.2177	0.1924
	Kobe	0.1777	0.2905	0.3812	0.4125	0.3996

demonstrate the effectiveness of base isolation in reducing the seismic vulnerability of this structural system. In addition, the relative accelerations and hence effective shear forces on the TRCWs were reduced by reducing the maximum drifts in the RCWT building by using U-FREI devices as base isolation systems. This reduces the vulnerability of this type of ultrathin wall to flexural compression and out-of-plane buckling effects, which is a characteristic deficiency of these structural elements (Arteta et al., 2014, 2018; Cheng et al., 2023; Ortega et al., 2023).

On the other hand, the maximum lateral base displacements generated by U-FREI devices used as a base isolation system for all seismic events assessed are identified in Table 6, and shown in Figure 16 (left). The Chihuahua earthquake presented a synchronization phenomenon with the dynamic behavior of the base isolation system, which generated an increase in the base amplitudes of 58.24% in comparison with the average of the other seismic events. The ADE during the RTHS test was obtained for the U-FREI devices and TRCW-M3R10 specimen, as shown

in Figure 16 (right). This indicates that the seismic isolator dissipates a large amount of energy owing to its viscoelastic behavior, and the ultrathin reinforced concrete wall dissipates a significant amount of energy because it remains within the elastic range.

Evaluation of the RTHS performance

Some indices have been proposed to assess the performance of the RTHS owing to inherent factors that introduce errors between the interaction of the transfer systems and the numerical and experimental substructures. The evaluation of local performance was based on the synchronization of the boundary conditions between the numerical response ($u_{i,d}^*$) sent to the actuator and the displacement achieved in the physical component ($u_{i,m}^*$). The normalized root-mean-square error in the experiment (NRMSE) can be used according to equation (5) to obtain a single value that represents the difference between actuator signals in the time domain. Similarly, for comparison in the frequency

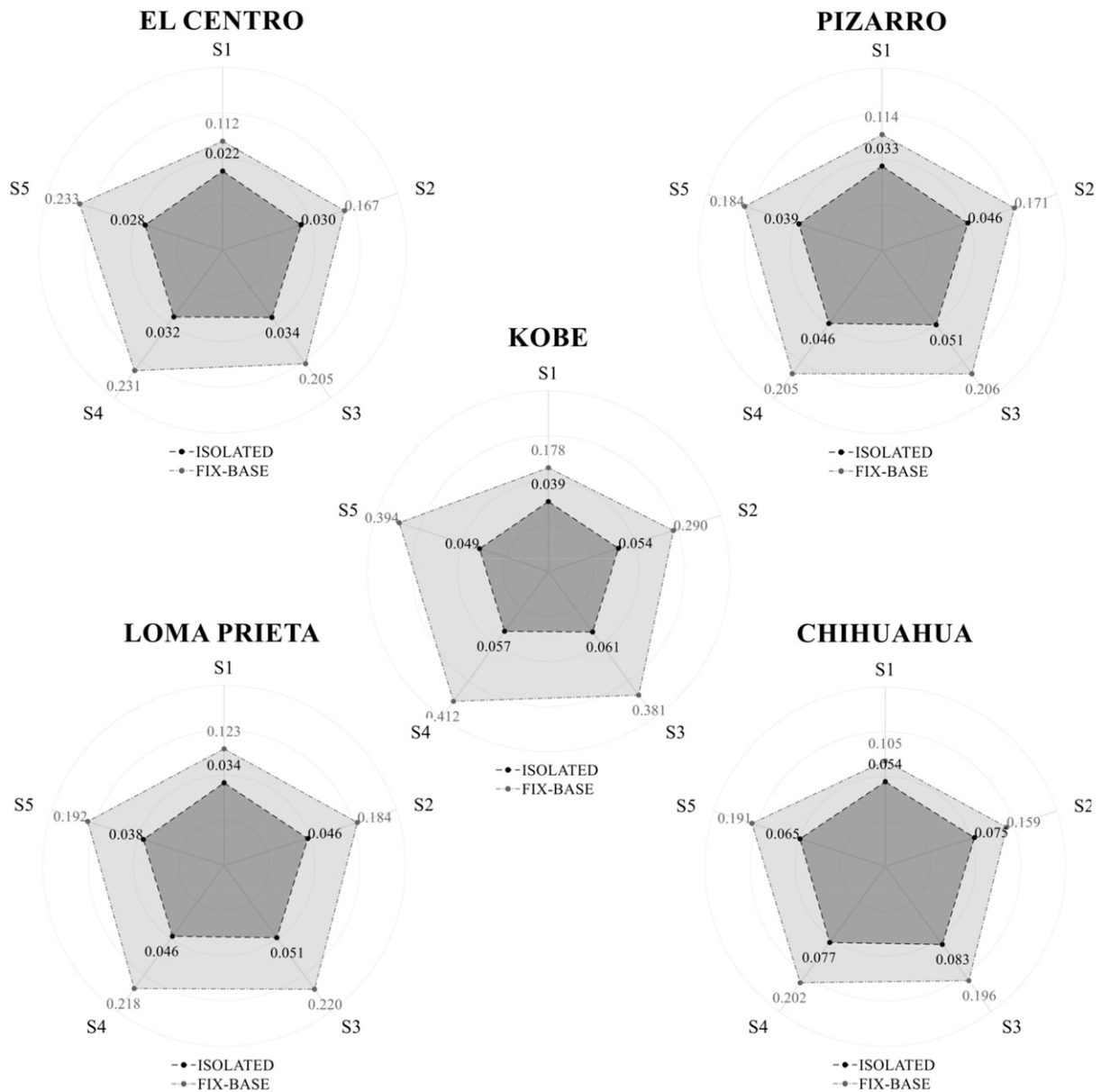


Figure 15. Inter-story drifts per level of the reference low-rise TRCW building. Isolated and fixed-base structure for all seismic events evaluated.

Table 6. The maximum lateral base displacements generated by U-FREI devices used as a base isolation system.

Seismic events	El Centro	Pizarro	Chihuahua	Loma Prieta	Kobe
Displacement (m)	0.137	0.257	0.614	0.268	0.366

domain, Equations (6)–(10) were considered, corresponding to the frequency evaluation index (FEI), which compares the fast Fourier transform (FFT) of the desired signal $u_{i,d}^*$ with that of the measured signal $u_{i,m}^*$ at the actuator, the frequency with the largest share

during the RTHS f^{eq} , the generalized amplitude A_0 , and the delay δ (Nakata et al., 2014).

$$NRMSE = \sqrt{\frac{\text{mean}((U_{a,d}(t) - U_{a,m}(t))^2)}{\text{variance}(U_{a,m}(t))}} * 100 \quad (5)$$

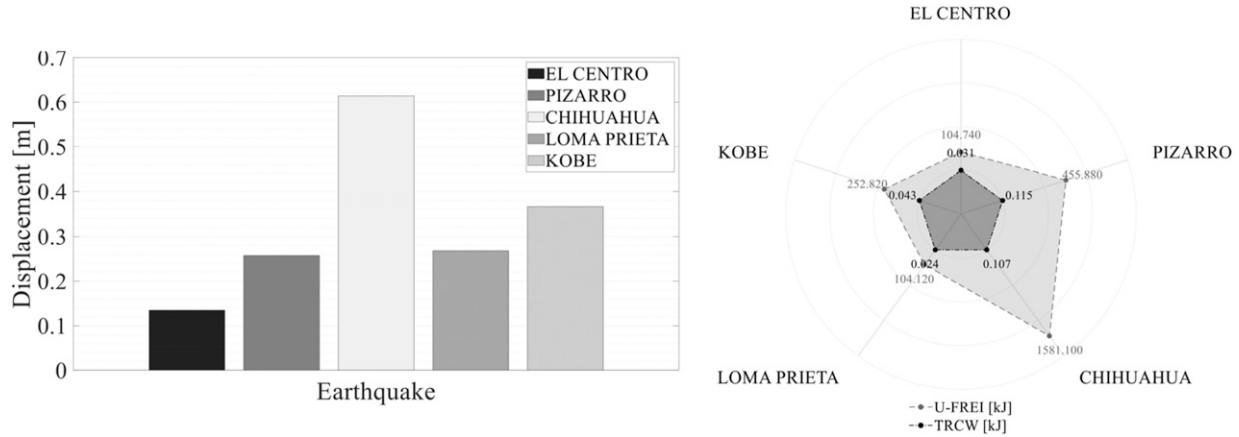


Figure 16. Displacement at the base level of the low-rise TRCW building (left) and accumulative dissipative energy of the experimental structural elements (right).

Table 7. Indexes of the RTHS on the SS-IF and THF.

Seismic event	FEI	f_{eq} (Hz)	A_0	e_{DM} (%)	e_{MD} (%)	δ (ms)	NRMSE (%)
Small-scaled isolator Framework (SS-IF)							
El Centro	1.006–0.040i	1.59	1.01	2.50	4.16	4.00	3.34
Pizarro	1.002–0.030i	1.01	1.00	0.35	2.35	4.60	2.63
Chihuahua	0.995–0.020i	0.74	1.00	0.52	2.92	4.30	3.22
Loma Prieta	1.015–0.031i	1.06	1.02	1.28	2.93	4.50	5.86
Kobe	0.998–0.031i	1.01	1.00	0.0042	3.39	4.90	3.19
Testing and homologation framework (THF)							
El Centro	0.5267–0.083i	1.97	0.54	11.62	43.31	12.6	65.39
Pizarro	0.7360–0.079i	1.40	0.74	5.04	22.41	12.1	64.23
Chihuahua	0.8175–0.062i	1.10	0.82	7.62	14.71	10.9	21.35
Loma Prieta	0.7997–0.080i	1.46	0.81	3.08	15.30	10.9	29.03
Kobe	0.8393–0.088i	1.48	0.85	4.71	14.58	11.3	24.38

$$FEI = \sum_{j=1}^N \left\{ \frac{y_m(j)}{y_c(j)} \cdot \frac{\|y_c(j)\|^l}{\sum_{i=1}^N \|y_c(i)\|^l} \right\} \quad (6)$$

$$f_{eq} = \frac{\sum_{j=1}^N \{\|y_c(j)\|^l \cdot f_j\}}{\sum_{j=1}^N \|y_c(j)\|^l} \quad (7)$$

$$A_0 = \|FEI\| \quad (8)$$

$$\phi = \arctan[\text{Im}(FEI)/\text{Re}(FEI)] \quad (9)$$

$$\delta = -\frac{\phi}{2\pi f_{eq}} \quad (10)$$

calculated and measured displacements using e_{DM} and e_{MD} , as shown in equations (11) and (12) (Nakata et al., 2014).

$$e_{DM} = \frac{|\max(|U_{a,d}(t)|) - \max(|U_{a,m}(t)|)|}{\max(|U_{a,d}(t)|)} * 100 \quad (11)$$

$$e_{MD} = \frac{\max(|U_{a,d}(t)| - |U_{a,m}(t)|)}{\max(|U_{a,d}(t)|)} * 100 \quad (12)$$

In addition, the global indices considered the interaction between the numerical and experimental substructures, and were evaluated in the time domain, quantifying the largest difference between the

All indices were obtained for all seismic events evaluated using the RTHS technique on the HTS of the SS-IF and THF, as presented in Table 7. In the first framework, all cases evaluated presented high-performance tracking with amplitude generalization values A_0 close to 1.0, errors less than 4.50%, and time delays of less than 5.0 ms. Similarly, the THF exhibited a high level of response tracking for all seismic events with low fractional content, with A_0 amplitude generalization values close to 1.0, errors lower than

15.50%, and delays lower than 13.0 ms. This performance allowed to conclude that STs as HTS using a robust control type H_∞ , which includes time delay compensation in its algorithms, had high performance and allowed RTHS with a high level of accuracy with average maximum errors of less than 3.14% and 22.06% for SS-IF and THF, respectively. However, THF had higher noise levels of the instrumentation system and time delay due to the dynamic performance of the hydraulic actuator, which conditioned the overall performance of the transfer system. These results demonstrate the optimal capacity of transfer systems with robust control to perform the RTHS tests.

Conclusion

The seismic performance of a reference isolated low-rise thin reinforced concrete wall building was evaluated using the multiaxial real-time hybrid simulation (M-RTHS) technique through dynamic substructuring in three principal substructures. The first dynamic component was confirmed by a pair of small-scale unconnected fiber-reinforced elastomeric isolators (U-FREI), which were adjusted using a Bouc-Wen numerical model to simulate the base isolation system of the reference structure numerically and experimentally. The second component was formed by the experimental specimens denoted as TRCW-M3R10 structural element, which represented approximately 12.0% of the thin-walls in the first level. The last component was defined as the remainder of the low-rise TRCW building modeled as a 6-degree-of-freedom shear frame. Each substructure interacts with another substructure through a transfer system to simulate the boundary conditions using a sample time of 1024 Hz. In this study, the transfer system was composed of a testing and homologation framework (THF) and small-scale isolator framework (SS-IF) at the University of Valle, Cali-Colombia. The seismic evaluation of the reference structure using M-RTHS was performed implementing five historical seismic events: El Centro, Pizarro, Chihuahua, Loma Prieta and Kobe with a maximum acceleration of $7.36 \text{ m} \cdot \text{s}^{-2}$ (0.75 g). Hysteresis curves of both experimental specimens were obtained. The U-FREI devices exhibited viscoelastic behavior with a high energy dissipation capacity and the characteristic behavior of these control devices. Regarding the TRCW-M3R10 structural element developed elastic behavior with a low energy dissipation capacity. The main conclusions are as follows.

- (1) The isolated low-rise TRCW building using U-FREI devices as base isolator system had reductions in maximum drifts of 83.98%, 75.18%, 57.47%, 76.77% and 83.45% for The Centro, Pizarro, Chihuahua, Loma Prieta, and Kobe seismic

event, respectively, compared to the non-isolated building evaluated through analytical model. Because of this reduction in the maximum drift, the effective shear forces on the TRCW structural element were also reduced, which reduced the vulnerability of this type of ultra-thin wall to flexural compression and out-of-plane buckling effects. The results indicate the technical potential of base isolation using U-FREI devices to reduce the seismic vulnerability of TRCW buildings.

- (2) The experimental assessment was performed using the M-RTHS methodology, taking a 6-DOF model of the low-rise TRCW building as a numerical substructure, scaled U-FREI devices as base isolation system and TRCW-M3R10 specimen as experimental substructures. Initially, all cases evaluated presented high-performance tracking for SS-IF with amplitude generalization values A_0 close to 1.0, errors of less than 4.50%, and time delays of less than 5.0 ms. Similarly, THF exhibited a high level of response tracking for all seismic events with low fractional content, with A_0 amplitude generalization values close to 1.0, errors lower than 15.50%, and delays lower than 13.0 ms. The above results indicate that the RTHS exhibits high fidelity and accuracy.

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