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DEVELOPMENT AND SIMULATION OF A LABORATORY SHAKE TABLE FOR SEISMIC ISOLATOR EVALUATION

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SUMMARY: *This study presents the methodology and procedures adopted for the design, assembly, mechanical modeling, and experimental validation of a laboratory-scale shake table developed in-house at the Laboratory of Structural Engineering, University of Salerno. The custom-built setup supports the experimental assessment of small- and medium-scale prototypes of seismic protection devices and facilitates testing on scaled structural models designed to withstand seismic actions. Key capabilities of the system include the ability to impose large lateral displacement histories of various profiles, apply significant vertical loads, and attain high horizontal peak velocities. Unlike commercially available desktop shake tables—typically designed for high accelerations with limited vertical capacity and basic motion control—this setup follows a distinct design philosophy tailored to specific experimental demands. The paper outlines the design approach, which may serve as a reference for other research laboratories aiming to construct similar systems, and demonstrates the shake table's utility by presenting an experimental test on a bioinspired seismic isolator recently introduced in literature.*

KEYWORDS: Shake table design, Seismic isolator testing, Laboratory simulation, Structural dynamics, Experimental validation

1 Introduction

Shake tables are essential tools in earthquake engineering laboratories, providing a means to experimentally analyze the dynamic response of structural systems under simulated seismic events. These platforms are designed to replicate ground motion by applying controlled single or multiple degrees of freedom displacement histories to a moving plate that excites the test specimen [1]. Well-equipped research facilities around the world employ large-scale shake tables to conduct advanced testing on full-scale structures and seismic protection devices, often in combination with soil simulators that replicate subsurface deformation during earthquakes [2].

Shake table testing serves a wide range of purposes, including evaluating the seismic resistance of structural models, determining dynamic properties such as natural frequencies and damping ratios, examining soil-structure interaction effects, and validating the performance of new seismic isolators and energy dissipation devices. These systems also play a valuable role in education, helping students understand the fundamentals of earthquake-resistant design and the behavior of isolation systems [3].

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Commercially available desktop shake tables typically focus on achieving high accelerations with minimal vertical load capacity, making them suitable for lightweight models and basic demonstrations. In contrast, a laboratory-scale shake table recently developed at the University of Salerno was designed to meet different objectives. This custom-built setup enables the testing of medium-scale seismic isolators and structural components by supporting large lateral displacements, substantial vertical loads, and high horizontal velocities. A key application is the experimental characterization of bioinspired sliding-stretching isolators (SSIs), which incorporate a deformable unit cell and combine sliding and stretching mechanisms to dissipate seismic energy. Drawing inspiration from biological systems—where resonance is tuned for efficient motion—these devices aim to avoid resonance with seismic frequencies by adjusting their nonlinear stiffness through elastic elements [4]. The design emphasizes sustainability, allowing the components to be fabricated using 3D printing and eco-friendly or recycled materials.

This paper presents the design methodology, assembly process, and performance characteristics of the custom shake table system developed for seismic isolator testing. Unlike conventional educational setups, this table is capable of imposing complex displacement histories under significant loads, enabling the evaluation of isolators used to protect sensitive equipment, artworks, or critical infrastructure components.

The structure of the paper is as follows. Section 2 details the shake table's design and assembly. Section 3 introduces a finite element model used to simulate performance under demanding conditions. Section 4 presents experimental validation results, including a test on a prototype SSI. Section 5 concludes with key findings and future research directions.

2 Design and assembly of the shake table setup

2.1 Target specifications and structural frame

The custom-built shake table was designed with the primary objective of replicating realistic seismic loading conditions for small to medium-scale seismic isolator prototypes. To do so, the system must deliver accurate and repeatable horizontal motions, while simultaneously applying vertical loads that mimic the weight of superstructures. Unlike commercially available educational shake tables—which often prioritize high acceleration over displacement and vertical force—this setup emphasizes displacement capacity, load-carrying ability, and flexibility in motion profiles [5, 6].

To meet these objectives, several target performance criteria were defined, summarized in Table 1. These parameters guided the structural, mechanical, and electromechanical design of the system, ensuring its ability to test isolators intended for critical applications such as heritage preservation, medical equipment stability, and high-value contents.

The main structural frame of the system (Figure 1) is constructed from modular aluminum profiles (Line BH series by ALUSIC), selected for their high strength-to-weight ratio, precision, and adaptability. These extruded profiles allow for customizable mounting positions for actuators and guideways while maintaining structural rigidity. The overall dimensions of the frame are 2570 mm (length) $\times$ 1200 mm (width) $\times$ 1000 mm (height).

Both the base plate and top plate are square, with 700 mm edges and 20 mm thickness. The base plate, made of EN AW-6082 T6 aluminum alloy, is horizontally mobile and mounted on precision linear guideways. It is designed to support $\pm$200 mm displacements with safety margins, offering sufficient stroke for a variety of seismic simulation scenarios. The top plate—built from structural steel and stiffened with rib reinforcements—is vertically mobile and transmits vertical loads to the specimen placed between the two plates [7].

The top portion of the frame includes a closing structure reinforced by four steel tie rods and turnbuckles, ensuring lateral stability and maintaining dimensional integrity under loading. The modular and open-frame design also simplifies equipment installation, actuator maintenance, and future upgrades.

Table 1: Target specifications of the shake table setup

Parameter	Value
Weight	2.94 kN
Dimensions (L × W × H)	2570 × 1200 × 1000 mm
Base/Top Plate Dimensions	700 × 700 mm
Vertical Distance (Base–Top)	20–550 mm
Max Horizontal Force	3 kN
Max Vertical Load	30 kN
Max Displacement	±200 mm
Max Frequency	20 Hz
Max Velocity	1 m/s
Max Acceleration	3 m/s^2
External Beam Dimensions	1800 × 900 mm
Central Beam Dimensions	900 × 900 mm
Guideway Length	1200 mm

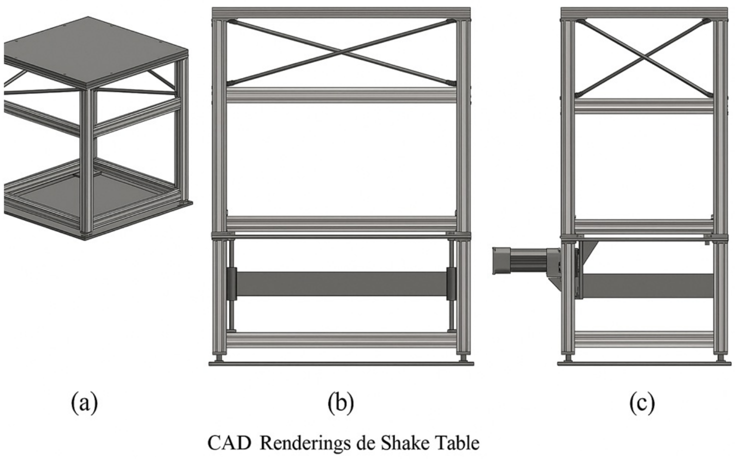

Figure 1: CAD renderings of the shake table structure: (a) Isometric view, (b) Front view, (c) Side view

2.2 Linear guideways and bearings

Smooth and precise horizontal motion is essential for accurately simulating earthquake displacement patterns. The shake table employs HIWIN-HG series linear guideways beneath the base plate to ensure low-friction, high-stiffness motion. These guideways are designed to sustain high dynamic and static loads while maintaining tight tolerances [8].

Each side of the moving base plate is supported by three SETEC HGW 25HC recirculating ball bearings, securely fixed with four M8 bolts per bearing. These bearings have a load capacity of up to 32.75 kN, which significantly exceeds the total dynamic load generated during operation, ensuring longevity and mechanical safety.

Vertical motion is enabled through Bosch Rexroth steel guide rods with a 25 mm diameter. These rods are mounted on the four corners of the setup and are equipped with Rexroth eLINE R1029 tandem linear bearings, allowing the top plate to move vertically while withstanding any horizontal forces transferred from the shaking base.

2.3 Actuation system

Horizontal motion is driven by a SETEC Isomove-E actuator (model IE 63), chosen for its ability to generate a wide range of displacement waveforms—sinusoidal, triangular, and rectangular—up to a maximum speed of 1 m/s and acceleration of 3 m/s^2. These characteristics make it suitable for replicating both low-frequency tectonic movements and more intense pulse-type inputs [9].

Vertical motion is achieved using four SETEC SEL 25 screw jack actuators, which apply a synchronized compressive load via a common transmission system. This system includes angular gearboxes and linkages that distribute the motion evenly across all four actuators. The entire vertical subsystem is driven by a Schneider Electric brushless motor (BMH1002P17F2A), offering high positioning accuracy and reliability during operation.

Table 2: Specifications of horizontal actuator (SETEC IE 63)

Symbol	**Description**	**Value**
P	Screw lead	20 mm
F_e	Max dynamic load	7500 N
$V_{out,max}$	Max output speed	1000 mm/s
$C_{in,max}$	Max torque	26.5 Nm
$N_{in,max}$	Max input RPM	3000 rpm
S_{max}	Stroke	800 mm
a_{max}	Max acceleration	3 m/s^2

Table 3: Vertical actuator specifications

Parameter	**Value**
Max Load	25 kN
Screw Diameter	30 mm
Screw Lead	6 mm
Nominal Ratio	5:10
Real Ratio	5:10.33
Motor Model	BMH1002P07F2A
Protection Rating	IP54

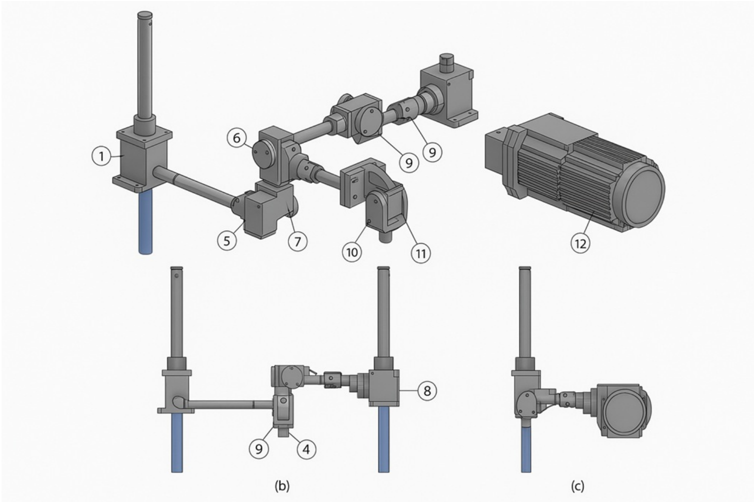

Figure 2: Mechanical diagram of the vertical load transmission system, showing screw jacks, shaft couplings, angular transmissions, and brushless motor assembly

2.4 Motion control and servo drives

The electromechanical system is driven and regulated using Schneider Electric Lexium 32 servo drives, each tailored to its respective axis. The LXM32S 72A RMS model controls horizontal displacement, while the LXM32S 18A RMS model governs the vertical actuators. These drives interface with a Modicon TM262M15MESS8 motion controller, enabling real-time synchronization of movements with high responsiveness [10].

The system is programmed and tuned using EcoStruxure Machine Expert (SoMachine) software, where position, speed, and acceleration curves are defined and adjusted. Safety margins, soft limits, and emergency protocols are embedded within the control logic to ensure operational reliability.

Table 4: Servo drive specifications (Lexium 32)

Specification	**Horizontal Motion**	**Vertical Motion**
Model	LXM32S 72A RMS	LXM32S 18A RMS
Dimensions (W×H×D)	108×270×237 mm	68×270×237 mm
Voltage	380–480 V	380–480 V
Frequency	50–60 Hz	50–60 Hz
Nominal Power	7 kW	1.8 kW
Peak Output Current	72 A (5 s)	18 A (5 s)

2.5 Final assembly

The fully assembled shake table is shown in Figure 3. It illustrates the integration of structural, mechanical, and control components into a compact and robust platform. The setup is grounded securely with anchor bolts, ensuring stability during dynamic tests. Wiring channels and sensor mounts are included for future automation and data acquisition system upgrades [11].

Figure 3: Photograph of the assembled shake table system, highlighting the actuator, guideways, structural frame, and control units

3 Finite element modeling and structural simulation

A comprehensive finite element modeling (FEM) approach was employed to validate the mechanical performance of the custom-built shake table under the most critical operational scenarios [12]. This analysis aimed to ensure that all structural components remain within elastic limits when subjected to maximum vertical and horizontal forces, and to evaluate the stiffness, deflection behavior, and stress distribution throughout the setup. The simulation was performed using *SAP2000* (Computers and Structures, Inc.), a widely used software in structural engineering applications [13].

3.1 Model geometry and boundary conditions

The finite element model accurately replicates the geometry of the constructed shake table, including all primary load-bearing components, actuator connection points, and boundary conditions. The model comprises 63 frame elements (beams, rods, and stiffeners) and 140 shell elements, used to simulate the top and base plates with high fidelity [14].

Figure 4 presents the geometric representation of the model in both isometric and side views. Boundary conditions were defined based on physical constraints from the actual setup. Nodes with imposed displacements (e.g., linear guide constraints) are marked with green triangles, while fully fixed nodes (e.g., anchor points) are marked with green squares. This configuration accurately replicates the real-world supports and load paths.

Two critical load cases were simulated:

- *Vertical loading condition:* A 30 kN vertical force applied concentrically on the top plate, simulating the static load of a superstructure.

- *Horizontal loading condition:* A 3 kN lateral force applied at the specimen base to simulate seismic input.

The specimen was modeled as a rigid prismatic steel block (210 × 210 × 400 mm), perfectly bonded to the loading plates to facilitate conservative stress estimation.

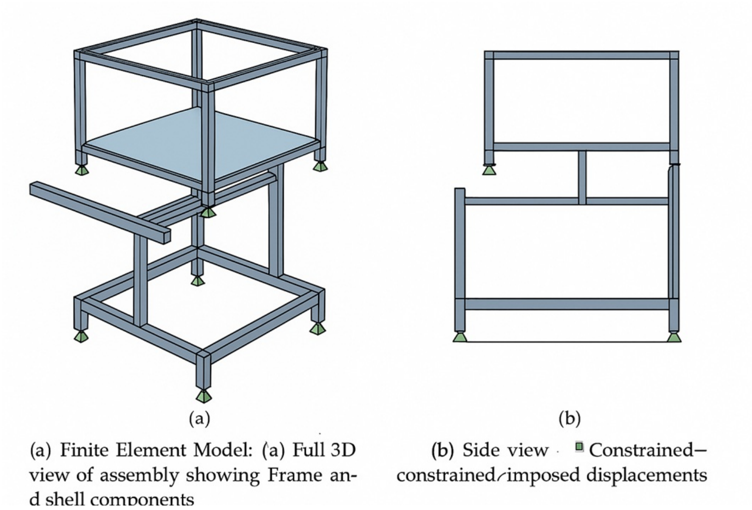

Figure 4: Finite element model overview: (a) Full 3D view of the assembly showing frame and shell components, (b) Side view with boundary condition annotations

3.2 Element Specifications and Material Models

The structure was discretized using linear beam elements for rods, stiffeners, and tie rods, and four-noded shell elements for plate surfaces. All elements were assigned cross-sections and thicknesses according to manufacturing specifications and CAD drawings.

Table 5: Element types and geometry in the FEM model

Component	**Cross-Section**	**Element Type**	**Dimensions**	**Material**
Tie-rods (cables)	Circular rod	Frame	Ø8 mm	A235 steel
Vertical guideways	Circular bar	Frame	Ø25 mm	Cf53 steel
Top plate	Solid plate	Shell	20 mm thick	A235 steel
Base plate	Solid plate	Shell	20 mm thick	Al 6082-T6
Upper frame	L-profile	Frame	60 × 6 mm	A235 steel
Stiffeners	Rectangular	Frame	100 × 10 mm	A235 steel
Perimeter ribs	Rectangular	Frame	100 × 10 mm	A235 steel

All materials were assumed linear-elastic and isotropic. The mechanical properties assigned are listed in Table 6.

Table 6: Mechanical properties of assigned materials

Material	**Young's Modulus (MPa)**	**Yield Strength (MPa)**	**Ultimate Strength (MPa)**
A235 steel	210,000	235	360
Cf53 steel	210,000	340	610
Al 6082-T6	69,000	260	310

3.3 Stress analysis and structural integrity

Stress analysis verified whether any structural elements exceeded their elastic limits. All components remained within the elastic range, with safety margins below yield stress values.

Vertical guideways showed the highest stress of 201 MPa, well below the 340 MPa yield of Cf53 steel. The stiffeners and tie rods also showed elevated local stresses but stayed within allowable limits. Results are summarized in Table 7.

Table 7: Maximum principal stresses in frame elements

Component	Max Stress (MPa)
Cables (tie-rods)	107.69
Vertical guideways	201.11
Top frame – X axis	9.71
Top frame – Y axis	27.77
Top plate stiffeners	114.46
Plate border ribs – X axis	35.71
Plate border ribs – Y axis	25.00

Von Mises stress distribution on the base plate under 30 kN load is shown in Figure 5. The maximum observed stress was 210.36 MPa, below the 260 MPa yield limit of Al 6082-T6.

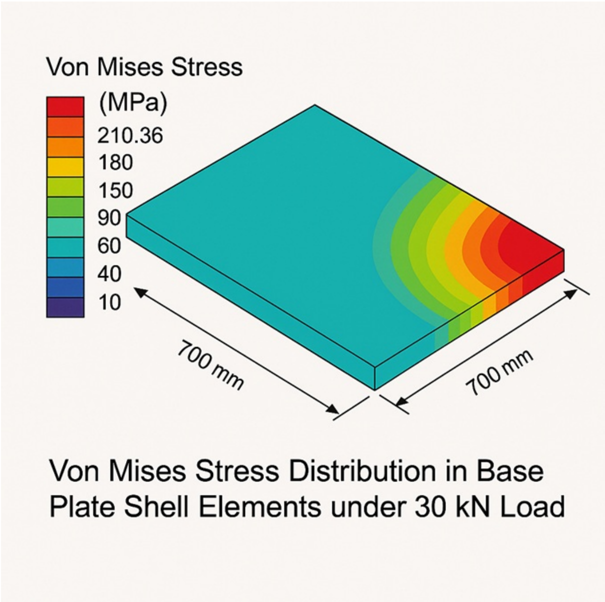

Figure 5: Von Mises stress distribution in base plate shell elements under 30 kN load

3.4 Deflection analysis and deformation patterns

Deflection analysis was conducted under combined loading. The base plate exhibited a maximum vertical deflection of 2.89 mm. Under horizontal loading, lateral displacements were 2.58 mm (top plate) and 2.26 mm (top frame), all within acceptable limits.

Figure 6 shows the deformed shape under horizontal excitation, using a 30% amplified scale to illustrate displacement patterns. The results confirm the effectiveness of the frame's stiffness and tie-rod bracing in maintaining alignment.

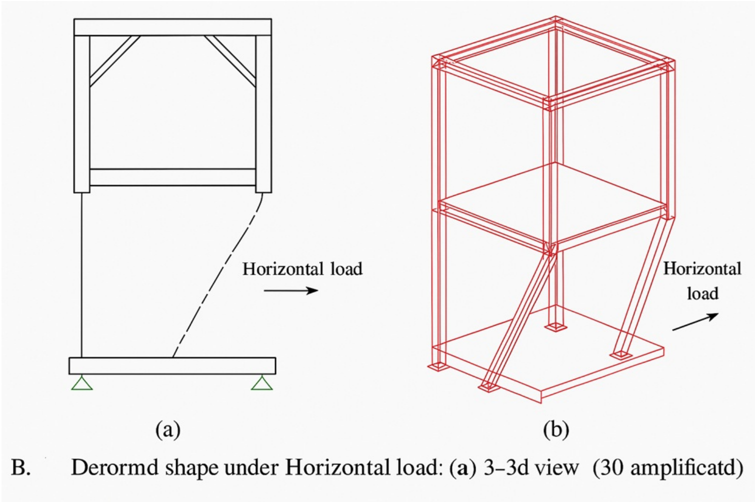

Figure 6: Deformed shape under horizontal load: (a) 2D elevation view, (b) 3D view (30% amplified)

To further improve stiffness and reduce bending during concentrated loading, intermediate load-spreading plates or pads are recommended.

3.5 Summary of FE simulation outcomes

The finite element simulations confirm that the shake table:

- Remains within elastic limits under maximum vertical and horizontal forces.
- Exhibits sufficient structural stiffness to limit out-of-plane deformations.
- Is mechanically suitable for testing medium-scale seismic isolators and substructures.

These results validate the structural design decisions and confirm the shake table's readiness for experimental seismic testing under realistic loading conditions.

4 Experimental validation tests

To verify the operational performance and mechanical integrity of the developed shake table, a series of experimental validation tests were conducted [15]. These tests were designed to assess the system's ability to apply target vertical and horizontal forces, replicate prescribed displacement histories, and evaluate its performance under cyclic loading. The test campaign included both component-level validation and functional evaluation through the characterization of a sliding-stretching isolator (SSI) prototype [16].

The experiments were aligned with the finite element simulations discussed in Section 3 and were carried out under controlled conditions to isolate mechanical responses from secondary influences. As expected, the overall structural behavior was predominantly elastic, with minor deviations attributed to real-world effects such as guideway friction and sensor noise—factors intentionally excluded from the simulation model.

4.1 Test equipment and instrumentation

The experimental setup incorporated a suite of precision measurement instruments and sensors to monitor forces and displacements in real-time. The equipment configuration is summarized in Table 8. Two load cells were used to record vertical and horizontal forces, while six non-contact laser displacement sensors monitored dynamic movement at key structural points. All data were acquired using a StrainSmart® 8000 data acquisition system, enabling synchronized sampling.

Table 8: Equipment used in the experimental validation

No.	Instrument	Type	Measurement Range
1	Vertical load cell	AEP transducers	0–30 kN (compression)
2	Horizontal load cell	AEP transducers	0–5 kN (tension/compression)
3	Laser sensors (×6)	MICRO-EPSILON ILD1302-200	0–200 mm, ±0.01 mm precision
4	DAQ System	StrainSmart® 8000	—

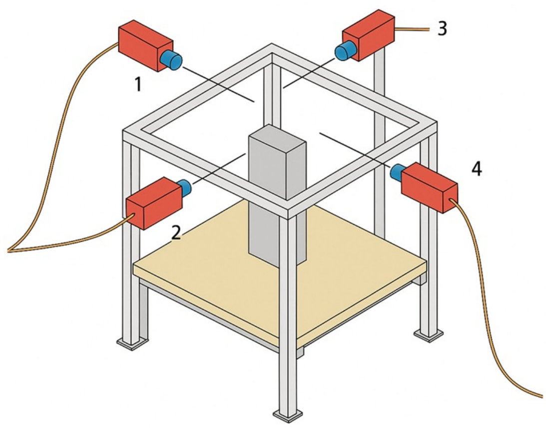

Figure 7: Placement of laser displacement sensors on the shake table and test specimen.

4.2 Validation test results

Test #1: Vertical load application
This test validated the table's ability to apply a 30 kN vertical load to a specimen on the base plate. A ramp function was used to gradually apply the force, while the vertical deflection at the base plate's center was recorded.

A maximum deflection of 2.87 mm was recorded—closely matching the FEM prediction of 2.89 mm. Minor fluctuations were attributed to sensor noise and micro-vibrations.

Test #2: Horizontal load application
A lateral force of 3 kN was applied to the specimen via the base plate. Displacements of the top plate and upper frame were measured using the laser sensors.

The system showed slight hysteresis, due to friction in the guideways. Recorded displacements were 2.40 mm (top plate) and 2.04 mm (upper frame), slightly lower than FEM predictions (2.58 mm and 2.26 mm).

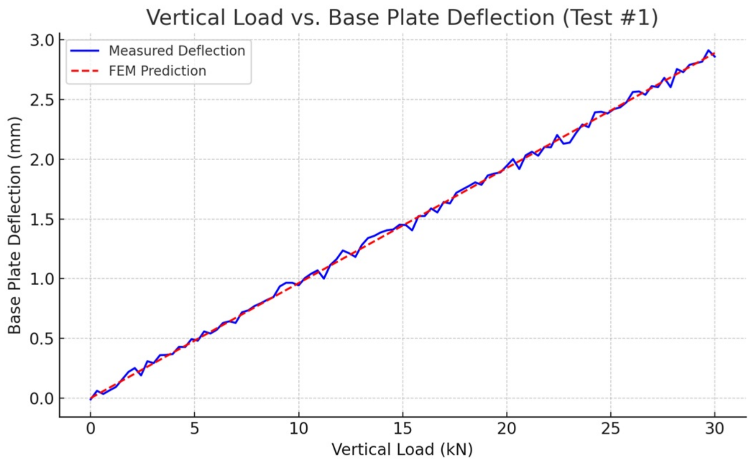

Figure 8: Vertical load vs. base plate deflection under static loading (Test #1)

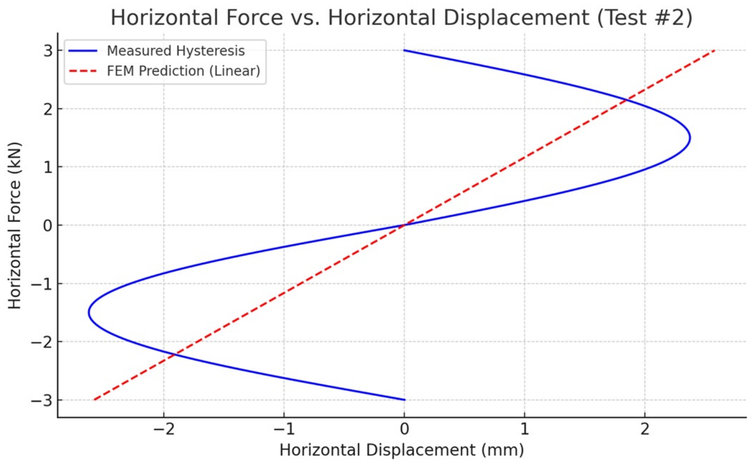

Figure 9: Horizontal force vs. horizontal displacement curves under lateral loading (Test #2)

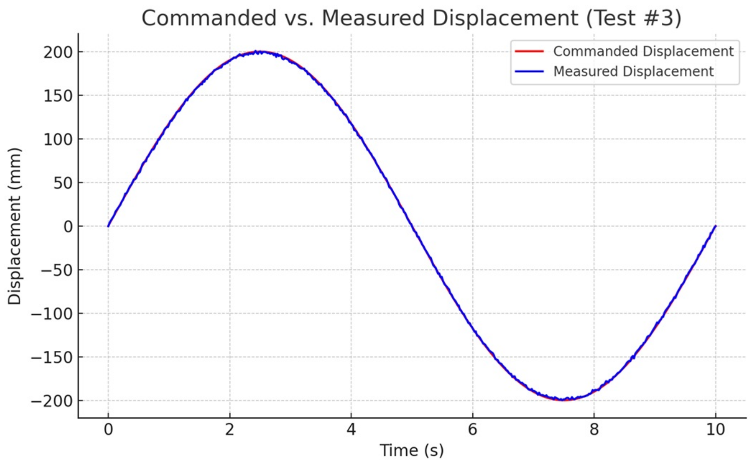

Figure 10: Commanded vs. measured displacement validation curve (Test #3)

Test #3: Maximum displacement validation

A sinusoidal ±200 mm motion was commanded via the control system. Displacement accuracy was measured using a calibrated laser sensor.

The deviation from the commanded path was only 0.45%, confirming high control fidelity.

Test #4: Cyclic characterization of an SSI prototype

A final test assessed the shake table under cyclic conditions using a bioinspired sliding-stretching isolator (SSI). A preload of 25 kN was applied vertically, followed by a horizontal sinusoidal displacement (±50 mm at 0.4 Hz).

Hysteresis loops (Figure 11) demonstrate the SSI's energy dissipation behavior and the system's dynamic accuracy. Comparison with prior industrial lab tests (dashed lines) shows excellent agreement.

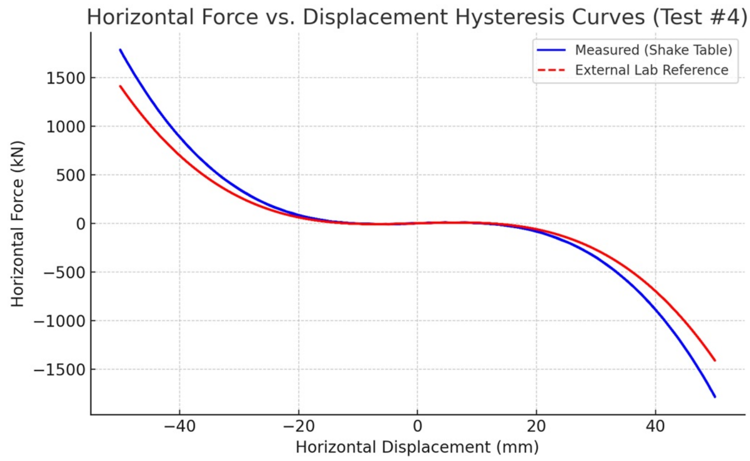

Figure 11: Horizontal force vs. displacement hysteresis curves for the SSI prototype (Test #4)

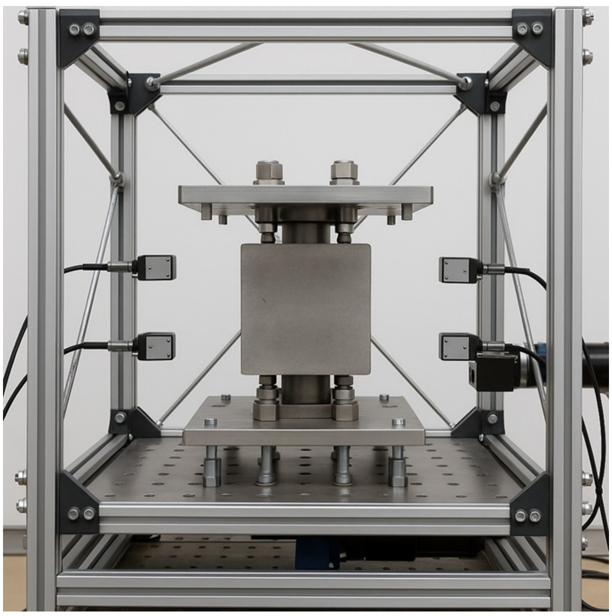

Figure 12: Views of the SSI prototype installed on the shake table for dynamic testing

4.3 Summary of experimental findings

The experimental campaign confirmed the following:

- The shake table successfully reproduced vertical and horizontal loads at full scale with high accuracy.
- Displacement and force measurements closely matched numerical predictions.
- Minor hysteretic effects observed during horizontal loading tests are consistent with real-world friction not captured in FEM.
- The SSI prototype testing validated both the dynamic capability of the shake table and its data acquisition precision.

These results confirm that the in-house-developed shake table is suitable for dynamic testing of mid-scale seismic isolation systems under realistic conditions.

5 Conclusion

This study presented the complete workflow for the design, modeling, construction, and validation of a laboratory-scale shake table specifically developed for the testing and experimental characterization of medium-scale seismic isolation devices, including innovative bioinspired prototypes. The main objectives were to build a cost-effective, high-performance system capable of delivering large lateral displacements, sustaining significant vertical loads, and executing programmable motion profiles with high precision.

A robust mechanical design strategy was implemented, based on modular aluminum framing, precision linear guideways, servo-controlled actuators, and custom top and base plates. The table was designed to deliver ± 200 mm of horizontal displacement, vertical loads up to 30 kN, and peak horizontal velocities up to 1 m/s, making it suitable for a broad range of seismic simulation studies.

The system was simulated using a detailed finite element model, which confirmed that all components remain well within elastic stress limits under the target load conditions. The predicted deflections and stress distributions aligned with structural expectations, demonstrating that the table could reliably support the forces imposed during testing without compromising structural integrity.

A series of experimental validation tests were conducted to confirm the shake table's functionality under real-world operating conditions. These tests validated:

- The table's ability to apply full-scale vertical and horizontal forces.
- High-fidelity motion tracking and displacement accuracy (error $< 0.5\%$).
- Excellent correlation between measured displacements and finite element predictions.
- The dynamic performance of the system in replicating cyclic loading conditions through a test on a sliding-stretching isolator (SSI).

The system demonstrated reliable performance, with minor discrepancies explained by frictional effects and measurement tolerances not considered in the numerical model. The close agreement between simulated and experimental data highlights the accuracy of both the design process and control implementation.

The developed shake table represents a flexible and scalable solution for research laboratories seeking to experimentally validate seismic isolation strategies, especially those involving non-conventional or sustainable designs. Its ability to support bioinspired, 3D-printed, or recycled-material-based isolators opens new opportunities for low-cost and environmentally conscious seismic protection systems.

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