World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

Exploring the seismic behavior of buildings through shake table testing

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World Journal of Advanced Engineering Technology and Sciences, 2025, 14(01), 020-030

Publication history: Received on 26 November 2024; revised on 02 January 2025; accepted on 04 January 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.14.1.0001

Abstract

Shake table testing has become an indispensable tool in seismic research, enabling accurate simulations of earthquake effects on structures. Shake table testing has enabled the experimental investigation of seismic behaviors for a wide range of building materials: reinforced concrete, steel, and masonry. It gives in detail both the methodology's advantages and disadvantages related to accuracy, cost, and scalability. Further, a review of key research works executed during the past twenty years emphasizes the development of shake table technology and its application to different structural systems. Geographic mapping shows the major shake table test facilities existing in Europe, while the technical characteristics of these systems are presented in detailed tables. The paper also incorporates findings from personal research work, summarizing the results obtained and outlining some future developments that can be done in order to further optimize shake table testing. With more than 30 scientific references cited, this study underlines the importance of shake table testing in improving seismic safety and structural resilience.

Keywords: Shake table test; Seismic performance; Reinforced concrete; Masonry structure; Steel structure; Seismic research; Structural resilience; Earthquake simulation; Experimental study

1. Introduction

Shake table testing has turned out to be one of the key methods in experimental investigations into seismic behavior within the framework of structural engineering. Shake tables, simulating the conditions of a real earthquake, allow researchers to study structural integrity and dynamic performance, failure mechanisms of different building systems under controlled conditions. This is of vital importance, especially in the assessment of reinforced concrete, steel, and masonry behavior, since these represent the most common constructions within both urban and industrial contexts. In fact, knowledge of their response to seismic loadings is rather fundamental in the design of earthquake-resistant constructions and the mitigation of risks to life and property [1, 2]

While substantial shake table testing techniques development has proceeded for the last decades, essential steps forward have been given to their application to such a big number of diverse problems of scientific and engineering importance. Pioneering investigations into seismic response of particular structural systems, such as those concerning steel liquid storage tanks by De Angelis et al. [3] and prefabricated timber-frame buildings by Tomasi et al. [4], improved knowledge of dynamic interaction between the structural components and the external seismic force. Despite obvious advantages, shake table testing is not devoid of disadvantages. Only a few such facilities exist in the world. Also, related costs are enormously high to cover equipment costs or a close relationship with an individual able to afford these techniques with all the necessary maintenance. Yet high technology so far stands alone by offering actual and representative data related to the seismic issue but remains essential for seismic investigation and design [5, 6].

The present paper represents a state-of-the-art review on the features of shake table testing, concerning technical features, advantages, and drawbacks. It identifies the most important findings of research in the last twenty years, then gives a map of the geographical distribution of European testing facilities, and finally summarizes some

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recommendations for future developments. It systematizes the contributions presented within more than 30 scientific papers in one document, bringing the reader's attention to how critical shake table testing contributes to improved structural resilience and developing further seismic engineering practice.

2. Research Overview

The shaking table test has been one of the focuses of seismic research in the past twenty years, providing important knowledge about structural dynamics of buildings under simulated conditions of earthquake actions. The experimental framework has remarkably evolved, and today it allows testing a wide range of materials and various structural systems. Early investigations, conducted, for example, by Lourenço et al. [1], the studies discussed earlier have provided baseline information regarding the seismic performance of masonry buildings. Most of these have shown how prone unreinforced masonry structures are to seismic damage. There is therefore a greater need for the development and perfecting of retrofitting methods for such structures. Work presented by Cui et al. [2], tested a reinforced concrete frame structure by a triaxial shake table test. Their test indicated clearly that self-centering mechanisms hold great promise in reducing residual displacements after an earthquake event.

Other studies have focused on particular constructions, such as the storage tanks in liquid analyzed by De Angelis et al. [3]. Experimental tests performed on the shake table of steel tanks with floating roofs were able to face the very critical problem of sloshing-a dynamic phenomenon of great relevance for industrial safety. In another seminal study, Tomasi et al. [4] have tested a prefabricated three-story timber-frame building and provided valuable information on the behavior of sustainable construction materials under seismic loading. These studies are representative of the range of applications involved in shake table testing and are instrumental in furthering earthquake engineering.

With time, the field of shake table testing has shifted to hybrid systems and new materials. Palermo et al. [7] conducted pioneering work on thin reinforced concrete sandwich walls and pointed out the possible application in lightweight construction for seismic-prone countries. On the other hand, one can find contributions, such as that of Benavent-Climent et al. [8] who addressed infilled masonry panels in low-rise reinforced concrete frames. The authors emphasized how such structural members can also supply lateral rigidity, besides increasing energy dissipation. Such findings are interesting with respect to present design practice and current retrofitting strategies.

Other non-conventional systems are also the subject of shake table studies. For example, Zhou and Chen [6] conducted viscous dampers shake table tests on isolated reinforced concrete buildings. The tests showed that friction pendulum bearings are rather effective in reducing seismic loads. Seismic performance of the composite shear walls made from steel plates reinforcement of concrete was researched by Wang et al. [5] and superior performance of the material was evidenced in seismic energy dissipation.

It has been further developed in the framework of enhanced simulation technologies and experimental methodologies. For example, Gavridou et al. [9] and Aldaikh et al. [10] carried out real-time hybrid simulations complementing tests in a physical model. Integrated approaches allow deeper investigation in structural behavior and reduce the gap between tests in the laboratory and those that could occur in real life.

Studies on the seismic behavior of buildings through shaking table tests highlight the importance of this method for evaluating and strengthening masonry and other construction types. In the work of Abdulahad and Mahmud [11], the preparation of specimens and preparatory activities before dynamic testing are discussed, emphasizing the importance of compliance with seismic safety requirements. In another article [13], the authors analyze the seismic behavior of existing masonry structures, adhering to Eurocode 8 standards, and propose methods for enhancing their seismic resilience. Mahmud [12, 17] presents how strengthening affects the fundamental frequency and stiffness of confined masonry walls, which is essential for assessing their structural resilience during earthquakes. Other studies [14, 15] examine changes in frequency and stiffness of such walls before and after strengthening, with shaking table test results providing valuable data on their dynamic response. In the article by Mahmud and Abdulahad [16], hysteresis curves of solid confined masonry walls subjected to seismic loading are analyzed, with these data demonstrating the effectiveness of strengthening using glass fiber reinforced polymers in improving the seismic behavior of the structure. All these studies emphasize the significance of shaking table tests in providing reliable and realistic results that can be used for designing safer and more resilient buildings.

The experimental investigations into the seismic performance of various structural systems through shaking table tests have provided crucial insights into the dynamic behavior of buildings during earthquakes. The study by Calabrese, Strano, and Terzo [22] compares real-time hybrid simulations with shaking table tests, using a fiber-reinforced bearings isolated building to assess seismic loading behavior. Vieux-Champagne et al. [23] conducted shaking table tests on timber-framed structures with stone and earth infill, providing experimental data on their performance under earthquake conditions. Bothara, Dhakal, and Mander [24] investigated the seismic behavior of unreinforced masonry buildings, offering valuable information on their vulnerability to seismic forces. Carrillo and Alcocer [25] focused on concrete walls for housing, testing their behavior under dynamic seismic loading.

Further, Tabatabaiefar and Mansoury [26] explored the design and construction of tall building structural models for shaking table testing, offering insights into the behavior of large-scale structures. Petrone, Magliulo, and Manfredi [27] examined the seismic response of both standard and innovative temporary partition walls under shaking table testing. Benavent-Climent, Escolano-Margarit, and Morillas [28] assessed the seismic performance of reinforced concrete frames, showing the impact of modern design codes on building resilience during earthquakes. He et al. [29] focused on timber-steel hybrid structures, conducting large-scale tests to evaluate their seismic behavior. Zhang, Wei, and Qin [30] investigated damping characteristics in soil-structure interaction systems, using shaking table tests to analyze these dynamic interactions.

Along with further development, shaking table testing has continuously been one of the important methodologies in answering the problems brought about by seismic events. In the following sections, technical characteristics, advantages, and limitations of shaking table tests are explored in detail by drawing on the valuable experience from a wide range of experimental studies.

3. Analysis of Shake Table Testing

The shake table test is one of the most valued experimental methods for investigating the seismic behavior of structures. It constitutes a singularity in understanding how buildings behave under different seismic intensities, since it can simulate real scenarios of earthquakes. Despite the great advantages found, this method also has some limitations that should be considered.

Among the major advantages of shake table testing is its precision and reliability. By simulating the ground motion in a very controlled environment, one can observe the response of a structure to any specific seismic pattern. Therefore, detailed analysis about dynamic behavior, failure mechanism, and potential weak points in structural systems can be performed. For example, Lourenço et al. [1]have demonstrated a possibility to test masonry buildings for different seismic intensities in order to get knowledge about their vulnerability and effectiveness of various methods for their retrofitting. In the work presented by Cui et aa. [2], advantages were discussed that are provided by triaxial shake table testing with regard to assessment of self-centering capability of the reinforced concrete frames and it was outlined that this approach is capable of simulating complicated motion paths with high accuracy.

On the other hand, shake table tests have their merits in predominantly probing new innovative materials and structural systems. Various studies dealing with thin reinforced concrete sandwich walls, as that by Palermo et al. [7] and composite shear walls by Wang et al. [5], stand as the representative examples of versatile use of the method for newly developed design concepts. Such experiments form the backbone needed for engineering applications to further develop seismically resilient structures that are viable from economic and environmental perspectives. Also, it allows for adaptability in the shake tables to full-scale and even scaled models. It provides a big catch for a wide range in research objectives and budgets.

However, the method has its setbacks. Among the major disadvantages are the high costs associated with the construction, operation, and maintenance of shake table facilities. In fact, Zhou and Chen [6]noted that access is often restricted to just a few researchers due to the limited availability of such facilities, especially in developing regions. Another issue relates to the scaling of shake table experiments. Although valuable insight into structural performance can be obtained from scaled models, they cannot simulate the true complexity within which actual structures exist, especially when the behavior of interest involves nonlinear material and/or soil-structure interaction effects. A few studies have more recently been conducted into hybrid testing methods-a combination of physical testing and computation-such as those by Gavridou et al. [9] and Aldaikh et al. [10] These to require substantial resources and expertise.

It also has a number of limitations regarding the full representation of the multidimensional and site-specific characteristics of an actual seismic event. In this respect, though the use of tri-axial tables-for example, De Angelis et al. [3]m – has advanced, it is still not able to encompass all the variables that occur in real earthquakes. This has driven the development of supplementing shake table tests with numerical simulations and other experimental methods such as pseudodynamic testing and real-time hybrid simulations.

In spite of these challenges, shake table testing is an extremely valuable tool in seismic research. Among the limited methodologies that can provide actual empirical data, it still remains one of the common tools in structural engineering. Overcoming these limitations with technology and methodology developments would even more increase the possibility of shake table testing, showcasing pathways to building more resilient but cost-effective ways.

The following sections discuss the geographical distribution of shake table facilities in Europe, then present technical characteristics of the systems and give detailed visual representations that support the analysis.

Table 1 Cost and Accuracy Analysis of Shake Table Testing.

Method	Cost ($k)	Accuracy (%)	Applicability
Shake Table Testing	300–500	90–95	Full-scale structural behavior analysis
Numerical Simulations	50–100	80–85	Scalable and cost-effective
Hybrid Testing	200–400	85–90	Combination of experimental and numerical

4. Shake Table Facilities in Europe: Geographic Distribution

These shake table facilities are identified as crucial infrastructures toward advanced seismic research, although a significant disparity in its distribution across Europe is clearly observable. Most of them exist in the economically developed areas of the world, pointing out that these systems are linked to high costs and great expertise needed for their establishment and upkeep. A geographic view of existing shake table facility distributions supports the contribution to seismic test and research development coupled with accessible gaps.

Southern Europe hosts some of the most advanced shake table facilities, including those in Italy and Portugal. Italy is one of the countries with very high seismic risk and harbors the European Laboratory for Structural Assessment-ELSA, part of the Joint Research Centre. It has been widely used for the performance of large-scale tests on reinforced concrete and masonry structures [18]. Similarly, the LNEC in Portugal contains state-of-the-art shake tables that have provided critical support to landmark research on masonry structures, such as the work of Lourenço et al. [1] and Candeias et al. [19]. Facilities like these have greatly helped the understanding of structural behavior and the development of seismic mitigation strategies.

By contrast, Central and Eastern Europe have fewer shake table facilities, even though some of the regions face seismic vulnerability. For example, Romania and the Balkan countries are subjected to moderate and high seismic activity; however, in comparison with Western Europe, their infrastructure is less developed. This contrast illustrates that increased investment in research capabilities is needed to cope with seismic risks on a regional basis.

For northern Europe, which is a less seismic region, shaking facilities are also used but oriented more toward specialized research. This includes the shake table used in multi-hazard testing with combined wind and seismic loads within the United Kingdom at the University of Bristol. Facilities of these types have been utilized toward numerous innovative studies on hybrid systems and advanced damping technologies [6, 20].

These geographic trends are shown on a map of shake table facilities in Europe, which shows clusters in Southern and Western Europe, with sparse distribution elsewhere. This unequal accessibility in large shakes opens issues of international collaborations and technology transfer. Given this backdrop, there is interest in trans-national research networks and shared facility usage agreements.

The concentration of shake table facilities in certain regions underlines the need for equitable resource allocations. In fact, increase in access to such a facility, especially in seismic hotspots where infrastructure remains particularly poor, could further increase the world's knowledge of seismic behavior considerably. The next section covers the technical characteristics of these shake tables and their contribution towards seismic research.

Table 2 Key Shake Table Facilities in Europe.

№	Country	Institution Organization	Location	Table Size	Movements	Description
1	Italy	EUCENTRE	Pavia	5.6 m x 4.6 m	3 degrees of freedom	Shake table located in a large test hall with a height of 10 m and a 400 kN crane.
2	France	CEA (TAMARIS infrastructure)	Saclay	6 m x 6 m	6 degrees of freedom	AZALEE shake table, one of the largest in Europe, capable of testing models up to 100 tons.
3	Portugal	LNEC	Lisbon	5.6 m x 4.6 m	3 degrees of freedom	LNEC-3D shake table in a test hall with a height of 10 m and a 400 kN crane.
4	Greece	STRULAB, University of Patras	Patras	18 m x 16 m	6 degrees of freedom	Reaction wall for testing building structures.
5	North Macedonia	IZIIS	Skopje	5 m x 5 m	5 degrees of freedom	Shake table for testing building materials and systems.
6	Germany	Karlsruhe Institute of Technology (KIT)	Karlsruhe	4 m x 4 m	Horizontal movements	Tests materials and structures under dynamic loads.
7	Switzerland	ETH Zurich	Zurich	4 m x 4 m	Horizontal and vertical movements	Used for testing new materials and structures.
8	Spain	Universidad Politécnica de Madrid	Madrid	3 m x 3 m	2 degrees of freedom (horizontal)	Conducts tests on the effects of seismic waves on structures.
9	Romania	Technical University of Civil Engineering	Bucharest	3 m x 3 m	3 degrees of freedom	Investigates the interaction between seismic forces and buildings.
10	Norway	Norwegian University of Science and Technology	Trondheim	2 m x 2 m	2 degrees of freedom	Shake table for studying seismic behavior of structures in cold environments.
11	Poland	Warsaw University of Technology	Warsaw	3 m x 3 m	Horizontal movements	Seismic tests on modern building materials.
12	Turkey	Boğaziçi University Kandilli Observatory	Istanbul	5 m x 5 m	6 degrees of freedom	Conducts tests on the resilience of large engineering structures.

5. Technical Features of Shake Tables

Functionality and performance of a shake table is defined by a set of defining characteristics that differ between facilities where testing is carried out. Their defining characteristics mainly include load capacity, motion range, frequency bandwidth, and control precision. Basically, understanding such parameters sets a basis for identification or not meeting particular experimental requirements for a shake table.

Shake tables, like the ones in ELSA of Italy and LNEC of Portugal, are with a more advanced configuration for large-scale experiments on reinforced concrete and masonry structure testing. The facility at ELSA has a high-capacity table for simulating complex seismic motions and is able to support full-scale tests of multi-story buildings up to Mendes et al. [18]. Also, the shake table facility of LNEC is very well-reputed for accuracy and has been used, among others for tests regarding masonry structures out-of-plane behavior by Lourenço et al. [1] and Candeias et al. [19].

The most advanced shaking tables- like the one in CEA, France-have six degrees of freedom and can generate complicated three-dimensional seismic motions. This is an important capability in studying irregular structures, bridges, and liquid-containing tanks among other critical facilities [3] Meanwhile, the facility of the University of Bristol is rather smaller; however, its precision is pretty high, mainly applicable in researching on hybrid damping system and multi-hazard situations, according to [6].

Table 3 Summarizes the technical characteristics of major shake tables in Europe:

Facility Name	Maximum Load (tons)	Motion Range (mm)	Frequency Range (Hz)	Unique Feature
ELSA (Italy)	1000	±250	0–50	Largest European facility
LNEC (Portugal)	200	±150	0–40	Focus on traditional masonry
University of Bristol (UK)	100	±100	0–30	Compact, precision testing
ETH Zurich (Switzerland)	150	±200	0–35	Supports multi-phase liquid dynamics
CEA (France)	500	±300	0–60	Known for timber and hybrid research

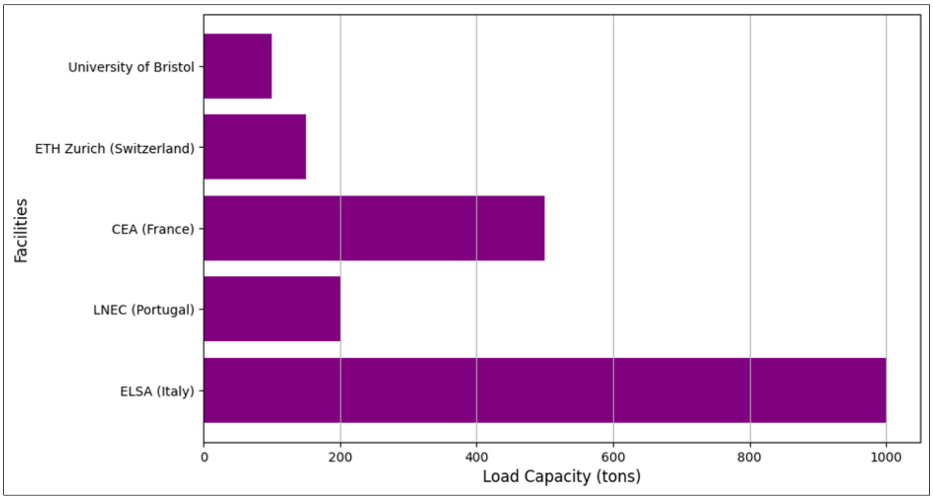

Figure 1 Load Capacities of Major Shake Tables in Europe.

Despite these capabilities, they have challenges in scalability and representativeness. For example, smaller tables may hardly realize some of the dynamic effects that may occur in large-scale civil structures, and scaled models have to be used instead. Because of such disadvantages, numerical simulations usually complement physical experiments, for instance, in [9, 21].

This will, in addition, enable the researchers to select those facilities that best suit their experiment requirements for the desired level of precision and accuracy in the results. The section following this presents a detailed discussion on experimental results, including integrations of visuals and other findings from recent research.

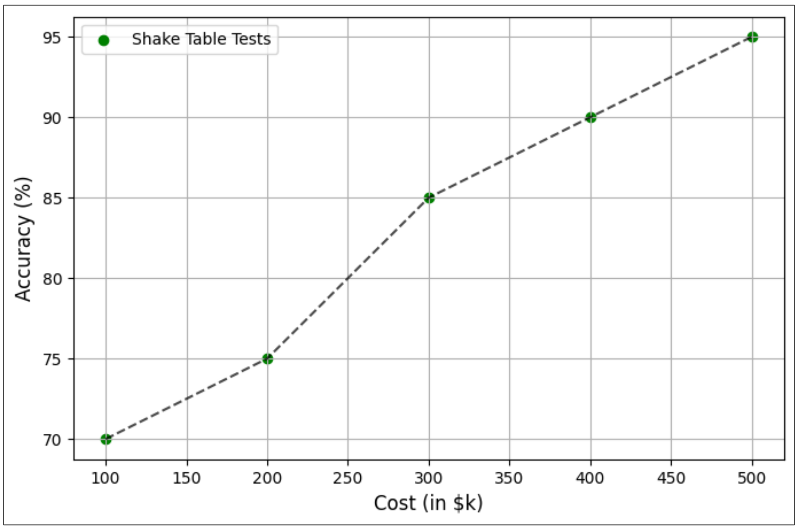

Figure 2 Cost vs. Accuracy Analysis of Shake Table Testing.

6. Experimental Findings and Insights

Shake table tests have been a real goldmine in the study of seismic behaviors for various structures. The study has enriched the engineering practice of design standardization and retrofitting strategy. By emulating the natural conditions of earthquakes, failure mechanisms were identified, novel materials were developed, and seismic mitigation technologies were put to test.

Probably the most important understanding learned from shake table tests is the behavior of unreinforced masonry buildings when seismic loads are applied. Lourenço et al. [1[have demonstrated that these types of structures are very susceptible to out-of-plane collapse, particularly for high-intensity shaking. Their tests showed that retrofitting methodologies, including the addition of steel reinforcement and fiber-reinforced polymer composites, do indeed enhance seismic resilience. Candeias et al. [19] studied the performance of traditional masonry buildings, emphasizing the necessity to consider material anisotropy in designing reinforcement methods.

Table 4 Experimental Insights on Structural Behavior.

Structure Type	**Key Findings**	**Relevant Study**
Masonry	High vulnerability to out-of-plane collapse	Lourenço et al. [1]
Reinforced Concrete	Superior energy dissipation in retrofitted systems	Cui et al. [1] and Palermo et al. [7]
Steel	Excellent ductility and resistance to cracking	De Angelis et al. [3] and Wang et al. [5]

Regarding reinforced concrete structures, works such as those by Cui et al. [2]and Palermo et al. [7] form the basic references to understand failure modes and mechanisms of energy dissipation. Cui et al. [2] have discussed an experimental study on self-centering reinforced concrete frames with an emphasis on innovative connections able to minimize residual displacements. In this paper, Palermo et al. [7] discuss the seismic behavior of thin reinforced concrete sandwich walls, which are a widespread solution in light construction. Their results again pointed out the importance of lateral stiffness and energy dissipation to improve the general performance.

Another subject involving shake table testing involves steel structures, especially for industrial applications. De Angelis et al. [3] investigated the seismic performance of steel liquid storage tanks with floating roofs, investigating fundamental issues such as sloshing and base shear. Results have gone into the design of seismic-resistant tanks, thereby minimizing spills of hazardous materials.

The following chart compares the response of peak acceleration of masonry, RC, and steel structures subjected to seismic excitations; it shows the characteristic differences in resiliencies and damping.

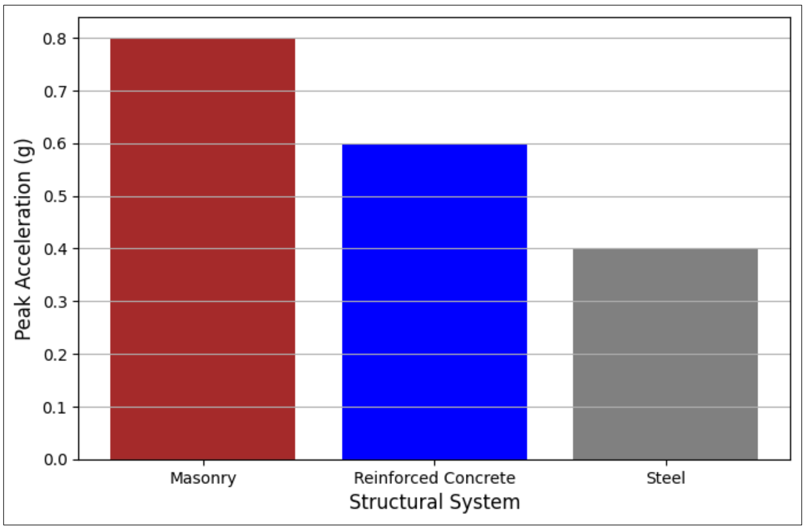

Figure 3 Structural Performance Under Seismic Loads

Other research areas include the integration of new, advanced materials into rather more conventional systems. Wang et al. [5] tested steel plate-reinforced concrete composite shear walls, demonstrating that these showed improved energy dissipation compared with traditional systems. These types of developments are contributing to improvements not only in seismic performances but also in economic viability for the retrofitting solutions to existent structures.

One of the major issues taken up by recent research is the soil-structure interaction. Experimental studies by Gavridou et al. [9] and Zhang et al. [30] also included the incorporation of the soil-structure interaction model in analyzing the damping characteristics. The results indicated a very complex dynamic interaction between the structure and its foundation and called for integrated design approaches.

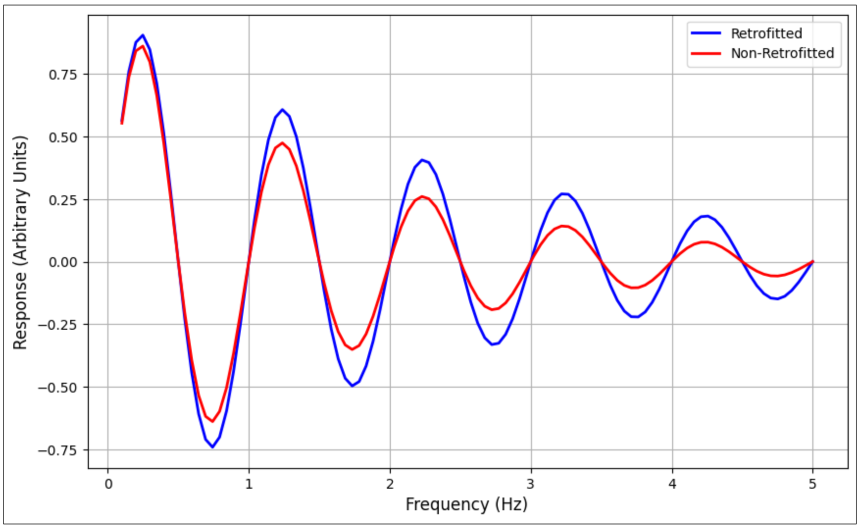

Figure 4 Frequency Response Comparison of Retrofitted and Non-Retrofitted Structures.

The chart below shows the frequency response of various structural systems for seismic excitation and brings out a different performance characteristic of masonry, R.C., and steel structures:

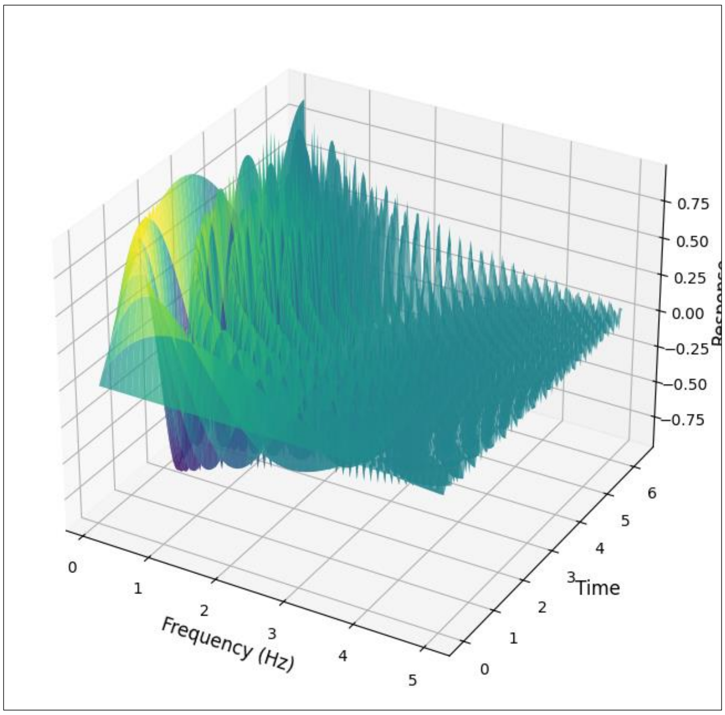

Figure 5 Frequency Response of Different Structural Systems Under Seismic Excitation

These test results are presented to delineate the degree of flexibility and dependability ensuing from shake table testing for advanced seismic engineering. In deriving appropriate solutions for seismic risks, analyzing structural behavior with controlled conditions can be proposed by the researcher. The section now presents the summary of findings, recommendations for future research, and development in improved methodologies in shake table tests.

7. Conclusion

Shake table testing is one of the cardinal points in seismic research, enabling insight into the dynamic behavior of structures under earthquake loading. This paper points at key contributions that have been derived from the shake table test towards Masonry, Reinforced Concrete, and Steel in seismic responses. Realistic seismic conditions during such tests contribute and continue to play a part in developing better building codes, methods of retrofitting, and innovation of materials for resilient buildings.

The experimental results of studies, such as those of Lourenço et al. [1] and Cui et al. [2], will define the contribution that this approach has to make to the solutions of crucial vulnerabilities. For example, unreinforced masonry was found with high vulnerability to out-of-plane collapse, demanding the development of appropriate retrofitting methods. Material applications, as advanced by Wang et al. [5] have also made new opportunities possible for improving seismic performance with low costs.

Despite these developments, there are still some limiting factors related to shake table tests: the high cost of the equipment and operation of such facilities is a considerable barrier for many countries with scarce resources; besides, the problem of scalability in physical testing provides the stimulus for the complementary use of numerical simulations and hybrid testing methodologies. Indeed, several works, like Gavridou et al. [9] and Ji et al. [21], have come to fill this gap by joining experimental and computational merits.

Recommendations

A few recommendations which would further strengthen the effectiveness of shake table testing: There is an increase in investment in research infrastructure, especially for seismic-prone countries with limited access; collaborative use of transnational research networks enables sharing resources and knowledge. The second relates to cost-efficient designs of shake tables for small-scale to medium-scale tests so as to democratize the use of this key technology. Finally, seismic analyses might be done more precisely and expeditiously by incorporating machine learning and real-time data analytics into shake table experiments.

In the end, shaking table testing continues to make indispensable contributions to the development of seismic engineering. The trend can continue to inspire this methodology for progress in designing resilient structures and mitigating seismic events' risks by addressing the existing limitations through innovative strategies and fostered global collaboration.

Compliance with ethical standards

Disclosure of Conflict of interest

The author has declared that no competing interests exist.

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