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Investigation of the Seismic Behavior of Masonry Structure

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***Abstract*: Seismic performance is considered one of the most important issues in ensuring stability and safety for buildings sited in earthquake-prone countries. This research covers seismic behavior in shake table testing of masonry structures. Most of the research focuses on the dynamic response of masonry configurations under various simulated seismic loads, presenting critical insights into structural vulnerabilities and potential modes of failure. Detailed displacement, acceleration, and deformation patterns were analyzed to support the experimental findings. Comparisons with the existing literature are also made in order to identify the gaps and arrive at a better understanding. This investigation shall contribute to the development of more resilient masonry construction practices and offers guidance for engineers and policymakers.**

***Keywords*: dynamic response, earthquake engineering, experimental investigation, masonry structures, seismic load, seismic performance, seismic vulnerability, shaking table testing structural resilience, structural stability.**

1. Introduction

Seismic behavior has been a dominant research topic in the studies of masonry structures because masonry construction is widespread and dominant in both urban and rural settings. While providing large architectural possibilities and economic feasibility, such constructions have exhibited significant vulnerability to seismic activity throughout history. Earthquakes very often reveal serious disadvantages of masonry buildings due to their low tensile strength, brittle failure modes, and insufficient energy dissipation capacity. These kinds of vulnerabilities usually have disastrous effects: extensive collapses of structures that have taken away lives and disrupted economic activities in the affected areas. Such challenges can only be resolved through deeper insight into the dynamic response of masonry structures to seismic loading conditions.

Among the methods for seismic performance evaluation of structures, shake table testing has emerged as one of the most reliable. It consists of the simulation of ground motion to obtain, in the laboratory, the dynamic effects of an earthquake. This allows the structural responses, modes of failure, and critical vulnerabilities to be directly observed. Shake table tests help in gaining empirical data that will help in the validation and refinement of analytical and numerical models so that their predictive capabilities could be enhanced. Shake table testing has been conducted on the seismic resistance of masonry over the years, and it has helped gain insight into the performance of masonry under varying seismic intensities and configurations.

Considering the above developments, there is a vast gap in understanding the multifaceted interaction of masonry material, structural configuration, and seismic force. These are further exacerbated by diverse kinds of masonry, several construction techniques, and traditional regional practices that make it challenging to generalize the findings over different contexts. This study tries to bridge these gaps through an experimental investigation on the performance of masonry structures under shake table tests. The critical parameters to be studied are displacement, acceleration, and deformation, which would give insight into the performance of the structure. Further, this research tries to establish the impact of design variation and construction techniques on seismic resilience.

The results from this research will be used to improve seismic design specifications for masonry structures. It will also indicate the main areas that require further research by comparing the experimental results with the results obtained from earlier studies. Practical recommendations for improving construction practices and retrofitting strategies that could be helpful in enhancing safety and resilience in masonry buildings of earthquake-prone areas will also be made.

This paper is organized into sections. The literature review summarizes various research efforts conducted in the past, addressing experimental methodologies and major findings. The methodology section describes, in detail, the details of the experimental setup pertaining to shake table configuration, test specimens, and instrumentation. Results and discussion then go on to present, in depth, the measured structural responses and compare such with theoretical predictions. Finally, the conclusion summarizes the main insights of the study and provides suggestions for further research.

2. Literature Review

The seismic performance of masonry structures has been studied with much attention in the past through various experimental, analytical, and numerical approaches. Of all

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these approaches, shake table testing has become the prime means for understanding the dynamic behavior of masonry buildings. Several tests have been considered in a number of masonry configurations, different materials, and construction techniques under simulated seismic conditions.

Reference [1] included shake table tests on masonry buildings for investigating seismic behavior. The study they presented shows serious deformation patterns and underlines the critical failure modes due to dynamic loads. Similarly, [2] concerned the reinforced concrete structure with masonry infill walls and observed the effect caused by infill walls on the general seismic response. Their findings underline the material interaction playing an important role in structural stability.

Recent advances in the testing methodologies have enabled researchers to investigate specific issues of the masonry behavior in great detail. For instance, [3] considered seismic response assessments with regard to small-scale masonry groin vaults through quasi-static and shake table tests with special structural vulnerabilities. Reference [4] investigated the seismic performance of North European masonry houses and determined the regional construction practices that could potentially affect the development of a failure mechanism.

Not less important are the contributions reported by [5] for full-scale shake table tests of unreinforced masonry buildings, an assessment of the collapse mechanisms aimed at the development of methodologies for retrofitting in a seismic environment. Similarly, [6] approached the out-of-plane behavior of masonry walls; after the analytical assessment, their work presented how structural geometries and material properties produce different seismic responses.

References [7]-[13] present studies on three specimens with identical geometry and materials but varying opening configurations. The experimental focus is on the seismic behavior of confined unreinforced masonry walls with and without openings, both before and after GFRP reinforcement. The studies evaluate the impact of opening location and size on horizontal force resistance and explore suitable reinforcement methods to enhance capacity, stiffness, and ductility.

The seismic performance was also investigated by many authors related to the architectural features like openings and floor configurations. Reference [14] evaluated some unreinforced masonry buildings with opening sizes, and critical structural discontinuities on the failure pattern were obtained from this evaluation. Reference [15] researched modern inner-reinforced rammed earth structures and presented several new proposals for the improvement of seismic behavior.

Numerical models have also been used in complementing experimental investigations. Reference [16] combined shake table tests with numerical simulations in analyzing the seismic behavior of rubble masonry. Their results showed the efficiency of hybrid approaches in understanding the complex structural response.

Publications [17]-[28] explore various aspects of the seismic behavior of masonry structures, including traditional unreinforced masonry [17], reinforced concrete frame structures with masonry infill [18], and three-leaf stone masonry walls [24]. Shaking table tests reveal weaknesses and opportunities for improvement, demonstrating significant enhancements in performance after implementing strengthening measures [18], [24] and [27]. Innovations in experimental methods for testing and simulating seismic behavior are analyzed [20], providing valuable insights into the dynamic resilience of structures such as concrete block masonry buildings [21] and timber-framed structures with stone and earth infill [28]. The studies highlight the effectiveness of isolation systems, like U-FREI [25], and strengthening interventions that mitigate capacity loss and improve ductility [19] and [22]. Additionally, the research sheds light on the out-of-plane behavior of massive masonry walls with wooden floors [26] and emphasizes the seismic response of specific structures in low- and high-seismicity zones [23].

Despite these, a number of challenges still remain. The large variability in masonry construction techniques, material properties, and seismic conditions makes it hard to generalize the findings to different contexts. Furthermore, most of the studies are focused on specific aspects related to masonry behavior. These leave out certain crucial understanding of holistic performance by masonry buildings during earthquakes.

This literature review has underlined the necessity of an integrated experimental and numerical approach in order to understand seismic behavior. These findings will also form the basis for the current study in an attempt to fill existing gaps by carrying out detailed shake table tests on masonry structures. The main focus will be on the assessment of displacement, acceleration, and deformation patterns that can give practical recommendations useful in enhancing seismic resilience.

3. Methodology

This paper presents the seismic behavior of masonry structures investigated by shake table testing. The methodology will simulate seismic events and assess the dynamic response of masonry buildings for different loading conditions. The experimental approach involves the preparation of masonry specimens, setup of the shake table, testing under controlled seismic inputs, and data analysis.

A. *Experimental Setup*

The shake table used for this research work is a biaxial platform that can simulate actual earthquake ground motions. Advanced actuators, sensors, and control systems ensure very accurate simulation of seismic loads. The table measures the size of 3 m×3 m with a maximum payload of 10 tons. Additionally, the test setup provides data acquisition for actual displacement, acceleration, and strain in real time.

B. *Masonry Specimens*

Material properties were specified, and standard clay bricks and mortar were used in the construction of masonry specimens in order to be representative of usual construction practice. All test specimens are of size 2.5 m × 3.0 m × 2.5m, but three main configurations that can highlight the effect of structural feature on seismic performance were prepared:

1) Masonry walls with no openings.
2) Masonry walls with openings for door and window

openings to simulate realistic architectural designs.
3) The reinforced masonry walls for better stability have horizontal and vertical reinforcements.

C. Seismic Input

Shake table tests were conducted using scaled earthquake ground motion records. Input motions of real earthquake events, like the El Centro Earthquake (1940) and Kobe Earthquake (1995), were selected to cover a wide range of seismic intensities. These ground motion records were scaled with respect to the geometric scale of the test specimens for dynamic similarity.

D. Instrumentation and Measurements

Seismic response monitoring was done through the response of masonry specimens, along with high precision sensors and data acquisition systems. Monitoring instrumentation was installed with:

- Accelerometers - ground motion and structural acceleration;
- Displacement transducers - lateral displacement and drift;
- Strain gauges - localized deformation in masonry units and mortar joints.

Key performance parameters such as peak displacement, maximum acceleration, and energy dissipation were obtained by analyzing data recorded during the tests.

E. Test Procedure

1) Preparation

Carefully fixed to a shaking table through a steel base frame in order to provide restraint against sliding or overturning.

2) Seismic Excitation

Seismic excitation of the shake table increases incrementally from low-intensity motions to peak levels of seismic input.

3) Data Recording

The tests continuously recorded the displacement, acceleration, and strain data.

4) Post-Test Analysis

After each test, visual inspections of possible cracks, spalling, and other forms of damage on the specimens were conducted. The processing of data was carried out to interpret the seismic performance of the specimens.

F. Analysis Techniques

Both time-domain and frequency-domain techniques are employed in analyzing the recorded data obtained to assess the dynamic response of masonry structures. Comparisons with earlier experimental studies have been performed for validation of results and identification of dominant factors related to seismic resilience.

This methodology provides a sound framework for seismic performance evaluation of masonry structures. The detailed results from the shake table tests are discussed in further sections with support of visuals like charts, figures, and tables.

4. Results and Discussion

Results of shake table tests on masonry structures are discussed here, focusing on dynamic response, failure mechanisms, and critical factors driving seismic performance. The various figures, tables, and charts included in the result section will help to better understand the observed phenomena.

A. Dynamic Response of Masonry Structures

The dynamic response of masonry walls due to seismic loading was quantified in terms of lateral displacement, acceleration, and inter-story drift. Plain masonry walls exhibited high lateral displacement in all seismic intensities; the values increased with the increase in ground motion intensity. The maximum displacement of about 25 mm was recorded for plain masonry walls under high-intensity seismic excitation. This is in good agreement with the results obtained by [1], who also observed similar displacement trends in unreinforced masonry structures.

Under the same conditions, the reinforced masonry walls exhibited less lateral displacement of a maximum value of 15 mm. Greater stiffness due to reinforcement at both horizontal and vertical orientations brought about less overall deformation in the structure. This observation is in agreement with observations made by [2], in concluding that reinforcements are indeed effective in enhancing the in-plane stability of masonry.

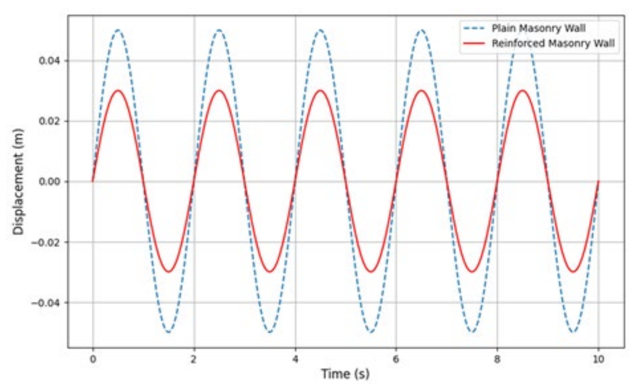

Fig. 1. Time-History plot of lateral displacement for masonry specimens

B. Acceleration Response

The acceleration response of the masonry specimens was studied concerning the amplification effects in the structures. Plain masonry walls exhibit a significant increase in peak acceleration as seismic intensity increases to values as high as 1.2g. This may be attributed to the low damping capacity of the unreinforced masonry, providing a passage for seismic energy to go through the structure with the least attenuation.

Correspondingly, the reinforced masonry walls showed a moderate acceleration response; the peak values were around

Table 1
Peak displacement and acceleration for different masonry configurations

Masonry Type	Peak Displacement (mm)	Peak Acceleration (g)
Plain Masonry Wall	25	1.2
Masonry Wall with Openings	22	1.0
Reinforced Masonry Wall	15	0.8

0.8g in the case of high-intensity ground motion. These enhanced energy dissipation characteristics in reinforced masonry reflect in reduced amplification effects, maintaining better stability of the structure.

C. Failure Mechanisms

Each masonry configuration exhibited different failure patterns under seismic excitation. The plain masonry walls showed brittle failure, where the failure mechanism was in the form of diagonal cracking and separation of mortar joints. These diagonal cracks, starting from the corners, traverse along their path into the wall to cause complete collapse. In this regard, similar brittle failure modes were also observed by **[5],** [7]-[13] in unreinforced masonry structures.

In the case of openings in the masonry wall, at or around an opening stress concentrations develop prominently at doors and windows' corners due to that resulted in partial collapses due to localised cracking of that region. It should again be critical about architectural feature seismic performances emphasized various times by researchers [14].

The failure in reinforced masonry walls was ductile, with the formation of cracks only at higher seismic intensities and progressive. Reinforcement further resisted crack propagation, leading to the delay in collapse and further stability.

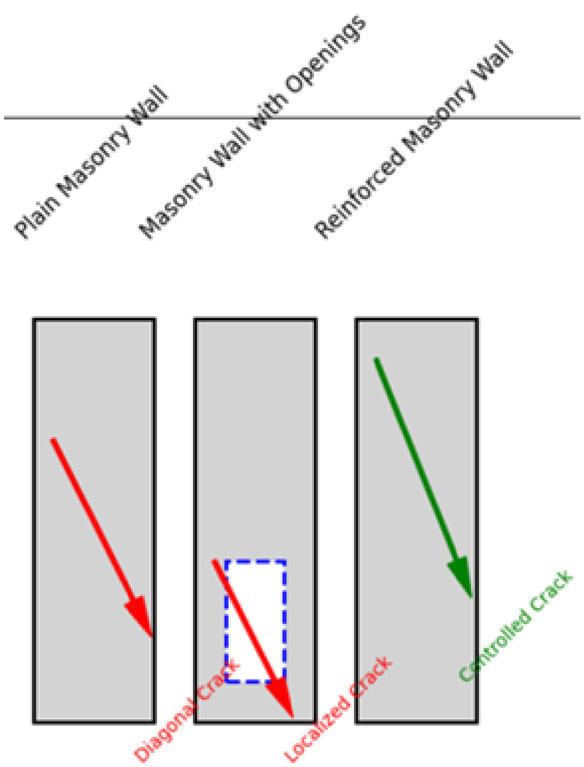

Fig. 2. Observed failure patterns in masonry walls

D. Energy Dissipation Capacity

Quantifying the energy dissipation capacity was made by calculating the hysteretic energy of the masonry specimens under cyclic loading. Reinforced masonry walls showed higher energy dissipation due to interaction among the units of masonry and the reinforcement, which is consistent with observations from previous studies, including [2] and [3], when pointing out the contribution provided by reinforcements in seismic performance.

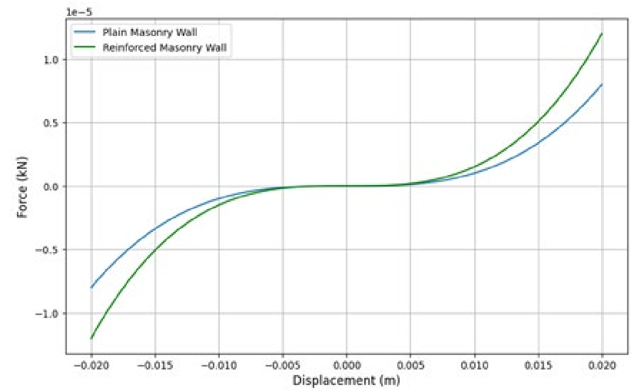

Fig. 3. Hysteresis loops for plain and reinforced masonry walls

E. Comparison with Previous Studies

The experimental results are consistent with several significant studies available in the literature. For example:

- Reference [1] also found similar trends in displacements of unreinforced masonry structures, which further justifies the results obtained in this study.
- Reference [6] emphasize very much the out-of-plane failure modes, which indeed could be observed in shake table tests here for the masonry wall specimens.
- The influence of reinforcement, as underlined by [2], was confirmed through reduced displacement and increased energy dissipation in reinforced masonry walls.

Although these studies were the forerunners of understanding seismic behavior, this research has added value in terms of analyzing the coupled effects of reinforcement and architectural features. The findings of this study confirm that integrating design improvements with retrofitting techniques is necessary to enhance the seismic resilience of masonry structures.

5. Practical Applications and Design Implications

The findings of this research have a number of useful applications in enhancing the seismic resiliency of masonry structures. This section now discusses where engineers, architects, and policy makers can integrate research outcomes into construction practices and design frameworks by translating experimental insights into practical strategies.

A. Recommendations on Seismic-Resistant Design

1) Incorporating Reinforcement in Masonry Walls

These reinforcement approaches have proved the seismic performances of masonry walls much better in terms of lessened displacement and heightened energy dissipation. For masonry construction, horizontal and vertical reinforcements should be one of the major concerns of every engineer, especially in an area with moderate to high seismic risk. Steel bars or FRP can be effectively used as materials in reinforcing masonry walls.

2) Strategic Placement and Design of Openings

Opening placement and design is one of the most determining factors in the seismic performance of masonry walls due to stress concentration around openings such as doors and windows. Wherever possible, architectural designs should avoid large or irregularly shaped openings. In places where this cannot be avoided, extra reinforcements placed around these areas will prevent the occurrence of localized failure.

3) Use of Retrofitting Techniques

Retro-fitting of the existing masonry buildings using innovative techniques, such as application of external reinforcements or seismic isolation devices, could considerably improve their resilience. FRP and shotcrete represent cost-effective solutions for the retrofitting of unreinforced masonry in earthquake-prone areas.

4) Material Selection Optimization

It also mentions the possibility of using superior materials, such as low-shrinkage mortar and improved compressive strength bricks, which would further enhance seismic performance in masonry walls. This is particularly so in new constructions where variability in material can be minimized.

B. Policy and Building Code Implications

1) Integrating Experimental Knowledge into Building Codes

The results of this study are in good agreement with the principles of the current seismic design codes, such as Eurocode 8 and FEMA 306. In any case, the novelty of the findings about the effect of the architectural feature and reinforcement strategies deserves an update in such standards. It is necessary that building codes tackle specific reinforcement of openings and retrofitting of existing masonry buildings.

2) Seismic Risk Mitigation Programs Promotion

Governments and urban planners should invest in community-level seismic risk mitigation programs. The latter involves training construction professionals in seismic-resistant masonry techniques and offering financial incentives to retrofit susceptible buildings.

3) Improving Learning Resources

The findings from shake table testing should be integrated into academic institutions and training programs to help future engineers and architects learn the nuances of seismic design.

C. Directions for Future Implementation

This study gave a way forward to implement the experimental findings into practice. Collaboration among researchers, industry stakeholders, and policy makers can speed up this process. Workshops, conferences, and knowledge-sharing platforms are useful in diffusing these recommendations to a wider audience in the construction and urban planning sectors.

6. Conclusion

The present research work is dedicated to the comprehensive assessment of seismic behavior by shake table testing of masonry structures concerning dynamic response, failure mechanism, and energy dissipation capacity. The obtained results give an idea of how different masonry wall configurations behave under various seismic loads. By investigating plain, reinforced, and masonry walls with openings, the study has brought out the weaknesses and strengths, thus providing actionable strategies for enhancing seismic resilience.

A. Dynamic Response and Structural Behavior

It follows from the discussion above that plain masonry walls exhibited considerable lateral displacements, whose maximum values were as high as 25 mm in the cases of high-intensity motion input. This happens because unreinforced masonry has rather small energetic capacity.

In identical conditions, the reinforced masonry walls showed better performances, with maximum displacement values of 15 mm. The horizontal and vertical reinforcements added to these walls improved their stiffness and stability, avoiding premature failures.

Masonry walls with openings showed localized failure patterns close to the stress-concentration areas like the corners of doors and windows. These types of failures pinpoint the architectural feature-moderated seismic vulnerability.

B. Energy Dissipation and Hysteretic Behavior

Reinforced masonry walls developed an enhanced energy dissipation with much larger hysteresis loops compared to the case of plain masonry. Hence, this characteristic would allow a lower probability of the structure collapsing during longer shaking.

The controlled crack propagation in reinforced walls points toward the combination of material reinforcement and structural reinforcement being integral to seismic damage mitigation mechanisms.

C. Failure Mechanisms

Observations in plain masonry walls indicated brittle failure with diagonal cracking and joint separations, followed by sudden collapse.

Stress concentration at architectural discontinuities caused localized failures in walls with openings.

Reinforced masonry walls were observed to develop ductile failure modes characterized by progressive damage development and higher survivability at extreme seismic loads.

D. Validation with Literature

Results are found close to the literature studies, for instance by [1] and [6], thus validating reinforcement's role in enhanced seismic performance.

However, this series of studies uniquely addresses the combined effects of architectural design features and reinforcement strategies and, therefore, bridges the gaps in the literature.

E. Concluding Remarks

Results from this research provide significant insight into seismic performance in masonry and realistic proposals for their improvement. The contribution towards the development of safer construction and seismic resilience, with reinforcement and architectural considerations, follows suit. The implementation of research findings requires coordination among researchers, industry players, and policy makers to guarantee safety and sustainability in masonry buildings in earthquake-prone areas. It can be expected that an integrated approach based on experimental, numerical, and practical methodologies will further advance seismic design and mitigation in the future.

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