Benchmarking The Use of Shaking Table for Simulating the Earthquake Performance of Typical Residential Houses for Disaster Risk Reduction

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Abstract. This study presents a review focused on the role of earthquake shaking table simulation in understanding the potential risk of confined masonry structures of residential houses. Understanding the potential risk leads to mitigating earthquake hazard risk of the typical confined masonry structures of residential houses. The primary objective of this study is to assess the effectiveness of earthquake shaking table simulations in evaluating and mitigating earthquake hazard risk for confined masonry structures, particularly for the typical residential houses in the most rural areas in Indonesia. By exploring the existing research and case studies, this research seeks to identify critical factors influencing the performance and resilience of confined masonry structures during seismic events. Thorough literature reviews of different research papers on the earthquake simulation test on confined masonry were carried out. The studies include the loading models, the type of construction models, and the boundaries of the simulations. This understanding will facilitate identifying potential areas for improving designs, constructions, and retrofitting practices specifically targeted at enhancing seismic resilience in low-income communities. The outcomes will facilitate evidence-based decision-making, leading to enhanced seismic stability and safer residential buildings in these developing areas where confined masonry houses are more needed and vulnerable. Finally, the work of this study can assist in preparing the most appropriate specimen model of masonry structures, which are intended to undergo testing in the earthquake shaking table facility at the Tsunami and Disaster Mitigation Research Center (TDMRC) of Syiah Kuala University (USK).
Keywords: confined masonry, earthquake, shaking table, vulnerability, residential houses.

1 Introduction

Natural disasters pose significant challenges to the functionality of communities or societies at various levels, leading to losses and impacts on people, materials, economies, and the environment. Disaster risk reduction can be achieved by minimizing vulnerabilities and enhancing capacities. One way to do this is by choosing the right type of structural system of building especially residential houses. Indonesia is situated at the junction of three active tectonic plates, making many regions in the country prone to earthquake hazards. This geographical reality directly impacts the buildings in Indonesia, particularly in efforts to reduce the risk of losses and damages from potential threats.

Recent significant earthquake events in Indonesia, such as the 6.5 Mw Pidie Jaya earthquake (December 7, 2016), the 7.4 Mw Palu earthquake (September 28, 2018), the 6.5 Mw Central Sulawesi earthquake (July 26, 2021), and the 5.6 Mw Cianjur earthquake (November 21, 2022), indicate a high seismic vulnerability in building structures of residential houses, particularly those adopting masonry as structural systems. Given their non-engineered traits, residential building is mainly the most impacted from earthquake [1]

A masonry building is a building that has a wall system as a load bearer. The walls are layers of bricks bonded to each other with mortar (a mixture of cement, sand, and water). Generally, masonry buildings consist of confined masonry or unreinforced masonry. From some literature, confined masonry was first discovered in Italy after the 1908 Messina earthquake [2]; [3] and was introduced in Chile around 1930, after the 1928 Talca earthquake [4], and has since been promoted internationally. Confined masonry structural systems have been informally developed and claimed to have good performance from previous earthquakes [5]

Despite assertions of the confined masonry systems good performance, assumptions have been made that poor work practices contribute to the structural failures of these systems. [6], in a case study of the Maule, Chile Mw 8.8 (2010) earthquake, reported that the lack of stirrup restraint in tie-columns was a primary factor leading to widespread damage in many buildings. In addition, experimental studies by [7] found that the absence of lintel beams at wall and window openings could induce stress concentrations at the corners of the openings. This inhibits the wall pairs from generating a resistance mechanism known as the "diagonal strut action". This concept, introduced in building design guidelines [8] ; [9] ;[10] as well as various literature pieces [11]; [12]; [13], aims to simplify masonry design.

There were several attempts to measure the performance of the masonry structures duringearthquake, i.e. through structural analysis and simulation modelling. The earthquake shaking table can be very effective in assessing the dynamic response of structures. The Multi Axial Shaking Table (MAST) at the Tsunami and Disaster Mitigation Research Center (TDMRC) is one of the tools to understand the dynamic behavior of structural system. This facility can assist in modeling the performance of buildings and analyzing their resistance to seismic forces. This paper serves as a literature review, a part of study in benchmarking the use of shaking table in preparation for further works. Ultimately, it could be a preliminary study for setting up an earthquake shaking table test for masonry structures representative of Indonesian typology. This is expected to lead to a comprehensive observation of the response of masonry structures with Indonesian typology. Following literatures is about the use of shaking table test that had been done for simulating the perfirmance of masonry structures during earthquakes.

2 Shaking table study of confined AAC masonry buildings

This paper, titled "Shaking table study and modelling of seismic behaviour of confined AAC masonry buildings" by Tomazevic & Gams [1]. The authors examine how Autoclaved Aerated Concrete (AAC) confined masonry buildings react to seismic ground motion. They tested three residential building models, each having the same wall layout but varying in the type of floors and the number of stories. These models were subjected to uni-directional shaking table experiments.

To perform scaling, this research focuses on the mass distribution and stiffness of the model used and the actual situation must be similar and the stress in the brick wall or masonry compressive strength must also be similar. Thus, when these two parameters are met, similar seismic responses and failure mechanisms are possible and value conversions of the physical quantities used can be determined. The model used in this study was built at a scale of 1:4. The scale factors used can be seen in Table 1.

Table 1. Similitude scale factor

Physical quantity	Scale factor
Length (l)	$S_L = l_P/l_M$
Strength (f)	$S_f = f_P/f_M$
Strain (ε)	$S_\varepsilon = \varepsilon_P/\varepsilon_M$
Specific weight (γ)	$S_\gamma = \gamma_P/\gamma_M$
Displacement (d)	$S_d = S_L$
Fore (F)	$S_F = {S_L}^2 S_f$
Time (t)	$S_t = S_L\sqrt{S_\varepsilon S_f/S_\gamma}$
Frequency (ω)	$1/S_t$
Velocity (v)	$S_v = \sqrt{S_\varepsilon S_f/S_\gamma}$
Acceleration (a)	$S_a = S_f/(S_L S_\gamma)$

The dimension of all experimental models in plan were 1.71 x 2.19 m. The first model, a three-story building (M1), incorporated lightweight prefabricated slabs, while the other two models (M2 and M3), a three-story and a four-story building respectively, used reinforced concrete slabs. The M1 model was exposed to seismic activity along the symmetry axis, while the M2 and M3 models were tested in an orthogonal direction.

The model was placed on a vibrating table and simulated the N-S component of Montenegro earthquake, April 15, 1979 with a motion duration of 48 seconds, and PGA of 0.43 g. It can be highlighted that the ground motion is scaled with time compression factor of $S_t = \sqrt{S_L} = 2$. The acceleration amplitude remained unchanged.

Several outcomes can be inferred from this study. Firstly, the conclusion of the paper emphasizes the significant role of vertical tie-columns in the seismic performance of the confined masonry buildings. The tie-columns improved the resistance capacity of the walls, prevented disintegration at the ultimate state, and ensured the integrity of the structure up to collapse. Secondly, the shaking table tests confirmed that all buildings of the tested type and size will exhibit adequate seismic behavior if constructed as a confined masonry system. Lastly, the paper also concludes that by using a relatively simple numerical model, good agreement between the experimentally observed and calculated non-linear response of buildings of the tested type can be obtained

3 Strengthening of masonry structures

In the research paper "Evaluating Masonry Strengthening Techniques Using Shaking Table Tests for Earthquake Mitigation" by Ersubasi & Korkmaz [2], the authors explore various techniques for reinforcing masonry structures. The study is particularly relevant for countries like Turkey, Greece, and Iran, which are susceptible to earthquakes and where masonry buildings are prevalent, particularly in rural areas.

The researchers conducted experiments on 1/10 scale models of single-storey masonry buildings. They began with a reference specimen for comparison and then tested other specimens that incorporated various strengthening strategies, with the total of nine specimens. The results of these tests provided insights into the effectiveness of different strengthening methods.

The paper also highlights the difficulties in testing masonry structures under lateral loads, due to factors like local shear failure of bed joints and the distribution of the structure's mass along the wall height. To overcome budget constraints, the authors developed a cost-effective shaking table test setup. This setup produces sinusoidal motions with increasing frequency and accelerations, with the rotation frequency and platform motion adjustable via an AC motor controller.

This paper discusses the effectiveness of a 1:10 scaled masonry building on a one-story building using a uniaxial shaking table. Scaling is done due to cost limitations in making full-scale test specimens, so the scaling follows research from the literature that has been done. This study contains nine specimens, namely:

1. Reference specimen, Un-Reinforced Masonry (URM).
2. Specimen CF1, URM strengthened with vertical formation of CFRP
3. Specimen CF2, URM strengthened with horizontal formation of CFRP
4. Specimen CF3, URM strengthened with CFRP at the corner region
5. Specimen SwSP, URM with steel plate
6. Specimen strengthened with steel wire mesh
7. Specimen P1, P2, and P3, URM strengthened with post-tensioning

Based on this research, it is concluded that unreinforced masonry walls that are commonly used are very vulnerable to earthquake hazards. In addition, the paper discusses various techniques for strengthening masonry structures against earthquakes. Vertical and horizontal reinforcement can enhance resistance but doesn't address local shear failure. CFRP significantly improves resistance, but its application isn't seamless with adobe material and it's costly, indeed. Post-tensioning leads to more ductile behavior but its application was appearing too complicated to be adopted on-site. Thin steel plates can improve strength but require careful application to preserve the structure's appearance. The application of reinforcement using welded steel wire mesh can increase the strength by up to 40% compared to the reference specimen. It can be highlighted that in all reinforced specimens, sudden collapse behavior was prevented, and also the frequent formation of cracks above door or window openings indicates potential weakness and merits further investigation in future works.

4 Damage detection via modal analysis of masonry structures using shaking table tests

The paper titled "Damage detection via modal analysis of masonry structures using shaking table tests" by Pepi et al. [3]. The research focuses on the use of modal parameters to detect structural damage. The study primarily investigates the vibration-based damage detection method on masonry structures using shaking table and modal analysis.

The paper investigates two 2-storey building models: an Unreinforced Masonry (URM) model and a Confined Masonry (CM) model. Both models have dimensions of 3 x 3.5 m in plan and a height of 2.2 m for each storey. Both models were tested using a 3D shaking table of 4x4 m platform, at the ENEA laboratory in Rome. The similitude requirements were taken into account, i.e., geometric and time scales, in order to have some reference parameters. In particular, the dimensions of storey height, wall thickness, and openings were scaled by 1.5 with regard to typical full-scale masonry buildings. The CM model includes tie-beams and tie-columns with dimensions of 16x16 cm at the corners of the building and 10x16 cm around the door and window openings.

The shaking table experimental program included seismic and forced dynamic tests on the building models with added masses. The two building models were affected by the same sequence of increasing amplitude earthquake acceleration time histories in order to compare the dynamic response of the two different structural resisting systems, URM and CM. The reference earthquake was the Norcia strong ground motion recorded in October 30th, 2016, the strongest event occurred during the 2016–2017 Central Italy seismic sequence, which was characterized by a significant vertical component.

Due to the limited capacity of the shaking table used, additional mass in the form of steel plates was added to each of the two floors and the balcony. The purpose was to reduce the natural frequency and increase the seismic load on the structure. The total additional mass applied to the structure was 6400 kg. The reason by doing so was in order to reduce the pre-dominant natural frequencies and to increase the seismic load on structural system.

The two building models were subjected to Ambient Vibration Test (AVT) in three different configurations: outside the shaking table (AVT#1), inside the shaking table (AVT#2), and inside the shaking table with additional masses (AVT#3). This was done to study the effect of the interaction between the dynamic actuator system and the models. The natural frequencies and vibration modes of the two building models were estimated using the enhanced frequency domain decomposition (EFDD) method [4].

The damage indicator associated with Modal Assurance Criterion (MAC) [5] is used to quantify the eigenvector variations due to damage occurrence. The MAC values range from 0 to 1, with 0 indicating no correlation (likely damage) and 1 indicating a perfect match (unlikely damage).

The study's results involved the evaluation of AVT data through classical modal analysis. This analysis provided insights into the structural behavior of the two models. It allows for the detection of possible damage of specimens. By linking the information provided by the variation in natural frequency and comparing the performance of the two models, it was demonstrated that the CM model is more effective in withstanding seismic loads. The CM model exhibited an amplitude 1.5 times higher than that which caused cracks in the URM model.

5 Other studies

The study of earthquake performance in masonry structures has been a topic of significant interest in the field of structural engineering. A variety of experimental methods, including shake-table tests, have been employed to understand the behavior of these structures under seismic loads.

A study by Tomazevic and Velechovsky [6] provides a comprehensive overview of how to simulate shaking table test in observing behavior of masonry structures. Considering the limitation fo modelling masonry specimen, 1:5 scale represents the upper limit for reliable earthquake shaking table simulation, especially for masonry structures. The study emphasizes proper adjustment of the dynamic characteristics of scaled specimen to meet the similitude requirement.

Benedetti et al. [7] conducted a robust experimental program involving 24 simple masonry buildings subjected to 119 shake-table tests. The study aimed to understand the seismic behavior of existing masonry buildings and assess the efficiency of different strengthening techniques. This study highlighting the effectiveness of horizontal ties in preventing separation kind of failure of walls. In addition, simple retrofitting techniques such as by sealing the local cracks will significantly increase the lateral resistance.

The study by Miglietta et al [8] investigated the effectiveness of an innovative timber retrofit solution on two full-scale building specimens. The buildings, typical of the North-Eastern Netherlands, were tested on a shake-table at the EUCENTRE Foundation laboratories in Pavia, Italy. The timber retrofit was designed and installed inside the second specimen, providing a sustainable, light-weight, reversible, and cost-effective technique. The retrofit system can improve the global response of the building with increased lateral capacities of the masonry walls.

Gioffre et al. [9] presents the results of a series of shaking-table tests conducted on two-storey unreinforced (URM) and confined masonry (CM) buildings. The study aimed to compare the dynamic response and seismic performance of the two different construction systems. The buildings were subjected to seismic accelerations of increasing intensity, leading to performance states ranging from minor damage to near-collapse. The results highlighted the superior performance of CM buildings in withstanding dynamic loads, compared to URM.

In conclusion, these studies collectively emphasized the importance of shake-table tests in understanding the seismic behavior of masonry structures. They also highlight the potential of various retrofitting and strengthening techniques in enhancing the earthquake resistance of these structures.

6 Preparing a shaking table model

The literature review shows the effectiveness of using a shaking table in testing building structures. The characteristics of residential buildings in Indonesia, which generally use masonry structures, can be simulated using an earthquake shaking table at the USK TDMRC laboratory.

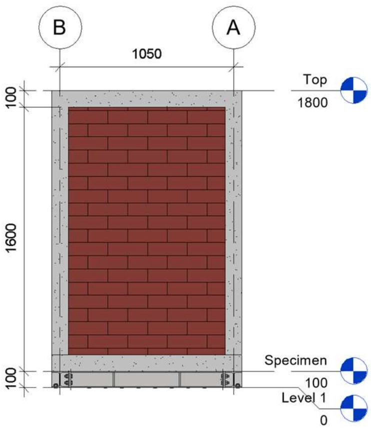
The dynamic response of a typical Indonesian masonry structure is set to be tested on an earthquake shaking-table, as depicted in Figure 1. This shaking table is a Multi-Axial Shaking Table (MAST), capable of simulating dynamic motion in a six-degree-of-freedom (6-DOF) system with a relatively high frequency (50 Hz) and a broad acceleration amplitude range (6 g). It can handle specimens up to 2 tons (maximum payload).

Fig. 1 Multi-Axial Shaking Table (MAST)

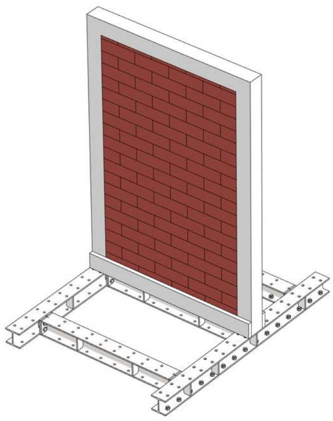
To date, by incorporating insight from the discussed references in this study, several considerations in developing shaking table model can be summarized as follows: (1) The similitude law has been identified as a critical aspect in shake-table testing. To mitigate the complexity of modifying the dynamic properties of materials (i.e., brick, mortar, rebar, and concrete) as well as the experimental setup (i.e., adding additional masses and safety brackets for collapse tests), it has been planned to conduct the model at full scale; (2) While the earthquake shaking table test of masonry structures has been thoroughly investigated in previous studies, especially in terms of their global response, the focus of this planned future work is to explore the least investigated aspect, such as the in-plane failure in the context of dynamic behavior of masonry structures; (3) This study aims to provide a unique perspective by incorporating both uni-lateral and vertical earthquake excitations, as most shake-table simulations have been conducted with uni-lateral vibrations; (4) While the CM structural system is recognized and adopted globally, the unique local variations in materials and workmanship practices across different regions may lead to inconsistencies in the performance of CM structures.

Therefore, this study aims to investigate a CM structure representative of the specific typology found in Indonesia.

To sum up, four unscaled masonry specimens, each with planar dimensions of 1 m in width and 1.5 m in height are scheduled for testing with typical setup as illustrated in Fig. 2. The first specimen represents an Unreinforced Masonry (URM) structure. The second specimen illustrates a Confined Masonry (CM) structure, in which the tie-column is built simultaneously with the masonry. The third specimen, also CM, will incorporate a rebar dowel in the connection between the wall and the tie-column. The fourth specimen is also a CM structure, but features a wall opening. Each specimen will be tested under uni-lateral and vertical earthquake excitations. The accelerogram data is inferred from the 6.5 Mw Pidie Jaya earthquake, Aceh, which occurred on 7 December 2016.



(a) Front view



(a) Perspective view

Fig. 2 Proposed specimen model

7 Conclusion

This study attempts to discuss the utilization of earthquake shaking table to investigate the dynamic response of masonry structure. This research will obtain a performance simulation framework for typical unconfined masonry buildings in Aceh to validate studies related to the resistance of residential buildings to earthquakes and obtain technical recommendations regarding structural systems for residential buildings with better seismic performance.

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