Centrifuge Modelling of URM Seismic Response Using Sand-Based 3D Printing

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ABSTRACT: Unreinforced masonry (URM) structures are particularly susceptible to seismic loading due to their inherently low strength and limited ductility. This study presents a comprehensive series of 29 centrifuge shake table tests conducted on identical small-scale physical models of a URM structure. Full-scale system-level testing under seismic conditions is often prohibitively expensive and logistically challenging, given the complexities of construction and facility requirements. To overcome these constraints, focusing on global-level modeling assumptions, 1:15 scale models were tested in the ETH Zurich Geotechnical Centrifuge Centre (GCC), ensuring dynamic similitude. The models were fabricated using additive manufacturing (3D printing) to replicate masonry-like elements. By modulating the micro-geometry of the printed components, the design effectively simulated mortar joints, enabling the use of a single printed material as a physical surrogate for traditional masonry construction. This paper details the specimen design, experimental setup, ground motion inputs, scaling principles, instrumentation, and key findings, including observed failure mechanisms. The test campaign serves as a benchmark for validating system-level assumptions in analytical and numerical models of URM structures subjected to seismic loading.

1 INTRODUCTION

Unreinforced masonry (URM) structures comprise a significant portion of the existing building stock worldwide, particularly in historical urban centers. Despite their widespread presence, URM buildings are known to exhibit poor seismic performance due to their limited tensile strength and brittle behavior. Understanding their dynamic response and failure mechanisms remains a critical challenge in earthquake engineering, especially for the validation of analytical and numerical models used in seismic assessment and risk mitigation.

Experimental investigation of URM seismic response at the system level (an entire structure) is inherently difficult. Full-scale shake table tests are expensive and logistically demanding, often limiting the number of specimens that can be tested and making probabilistic evaluation (which is necessary given the inherent uncertainties) impractical (Bachmann et al., 2018; Elmorsy, 2020; Vassiliou et al., 2021; Bao et al., 2022; Hassan and Elmorsy 2022a; 2022b; Elmorsy & Vassiliou, 2023a; 2023b; 2024; Elmorsy & Vamvatsikos, 2025). Reduced-scale testing offers an attractive alternative, provided that similitude of stresses and governing mechanisms is preserved. Geotechnical centrifuge modelling enables reduced-scale physical models to be subjected to appropriately scaled inertial forces, allowing global seismic response to be realistically reproduced.

A key obstacle in reduced-scale physical modeling of URM structures lies in specimen fabrication. Traditional masonry construction techniques become impractical at small scales due to manufacturing tolerances and labor intensity, often resulting in similitude distortion (Petry & Beyer 2012). Additive manufacturing has emerged as a promising solution to specimen fabrication challenges. Recent studies have demonstrated the feasibility of using sand-based binder jet 3D printing to fabricate masonry-like components, where mortar joints are emulated through controlled micro-geometric features rather than distinct materials (DeJong 2012; Ritter et al. 2016; 2018; Del Giudice et al., 2022; 2024; Elmorsy et al. 2024a; 2026). This approach enables the production of geometrically consistent and repeatable specimens while maintaining the ability to reproduce cracking and separation along predefined joint planes. Large-scale component-level tests remain necessary for precise component behavior evaluation (Del Giudice et al., 2020; 2022; Elmorsy et al. 2023; 2024a; 2024b; 2025a; 2025b; 2026a; 2026b).

Building on these advances, this study presents a centrifuge-based experimental investigation of the seismic behavior of URM structures, constructed using sand-based 3D printing. A total of 29 identical reduced-scale (1:15) models of a one-story URM building were fabricated and tested as virgin specimens at the ETH Zurich GCC (Elmorsy 2025; Elmorsy et al. 2026b). Each model was subjected to a distinct unidirectional ground motion derived from real records, enabling systematic evaluation of record-to-record variability in seismic response. Before the centrifuge model tests, material- and component-level experiments were conducted to characterize the mechanical properties of the 3D-printed material and masonry assemblies, providing a basis for interpreting the observed global behavior. The primary objectives of this work are: (i) to experimentally investigate the seismic response and failure mechanisms of URM buildings using centrifuge shake table testing; (ii) to assess the effectiveness of sand-based additive manufacturing for physical modeling of masonry structures at reduced scale; and (iii) to provide experimental evidence suitable for validating system-level assumptions, commonly adopted in numerical modeling approaches. The results also contribute to the advancement of physical modeling techniques for masonry structures.

2 EXPERIMENTAL PROGRAM

2.1 Specimen Design and Scaling

The tested structure is a reduced-scale physical model of a one-story URM building, inspired by previously tested masonry prototypes (Candeias et al. 2017; Mendes et al. 2017). The model was constructed at a geometric scale of 1:15. Centrifuge testing was employed to preserve stress similitude, with the time scale set equal to the length scale (1/15) and accelerations scaled by a factor of 15. The building consists of three masonry walls supported on a strip footing, with window openings in the North and West walls and an opaque East wall (Fig. 1). All walls have a uniform thickness of 15 mm (model scale). Masonry units were represented by prismatic blocks, the dimensions of which were selected to reproduce typical masonry proportions at reduced scale. Mortar joints were physically modeled by introducing vertical and horizontal notches of controlled geometry, forcing cracks to propagate along predefined joint planes (Fig. 2). This approach results in a masonry-like meta-material produced from a single printed material.

2.2 Additive Manufacturing of URM Models

All specimens were fabricated using a sand-based binder jet 3D printing process. The printing technique enables the production of geometrically consistent and repeatable specimens, while avoiding the construction challenges associated with traditional masonry at small scales. The joint notches were designed based on prior component-level investigations to reproduce realistic cracking and sliding mechanisms under low axial stress conditions. After 3D-printing, loose sand within the notches was removed using compressed air to ensure proper joint behavior.

A total of 29 geometrically identical specimens were tested at the GCC. The high repeatability of the 3D-printing process ensured that observed variations in seismic response are primarily attributable to differences in seismic demand rather than construction variability.

2.3 Experimental Setup and Seismic Excitation

The experiments were conducted using the geotechnical beam centrifuge of the ETH Zurich GCC, which is equipped with a state-of-the-art centrifuge-mounted unidirectional earthquake simulator (Fig. 3). Each URM model was fixed to the shake table through a 3D-printed strip footing and a steel clamping system that ensured stable boundary conditions, while allowing realistic inertial response.

Each specimen was subjected to a single unidirectional ground motion applied in the North–South direction. The input motions were selected from recorded earthquake accelerograms (Ancheta et al., 2013) and scaled according to centrifuge similitude laws (Harris & Sabnis 1999). A different ground motion was applied to each virgin specimen, enabling investigation of record-to-record variability in structural response and failure. Figure 4 depicts the pseudo-acceleration elastic response spectra ($\zeta = 5\%$) of the applied ground motions. Additionally, Table 1 summarizes the details of the applied ground motions.

2.4 Material and Component-Level Characterization

To support interpretation of the global seismic response, a series of material- and component-level tests were conducted on specimens produced using the same 3D-printing process. Uniaxial compression tests on bulk material samples provided elastic properties and compressive strength. Four-point bending tests were used to estimate tensile strength. In addition, masonry wallets and wall panels were tested under vertical compression and shear-compression loading to characterize stiffness, strength, and failure modes representative of the 3D-printed masonry assemblies. More details can be found in Elmorsy (2025) and Elmorsy et al. (2026b).

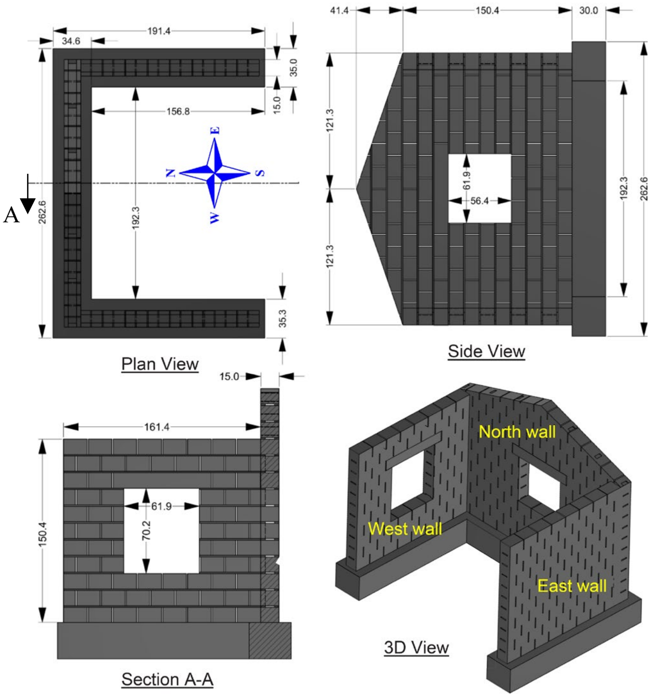

Figure 1. Geometry of the tested specimens (all dimensions are in mm).

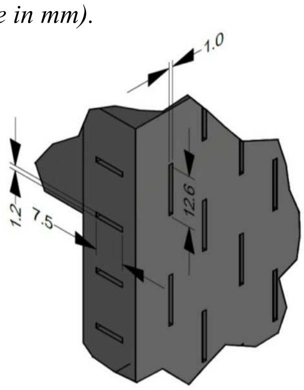

Figure 2. Vertical and horizontal notch details (dimensions are in mm).

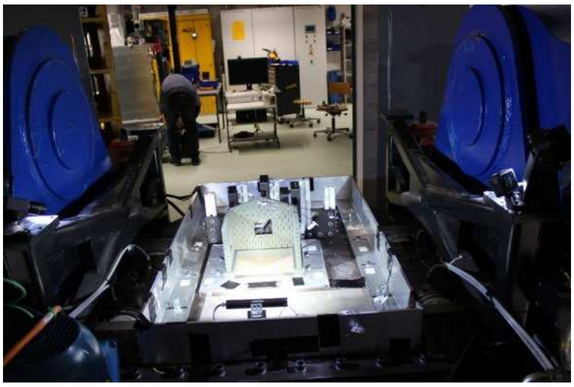

Figure 3. The ETH Zurich GCC beam centrifuge basket, showing the URM building specimen installed.

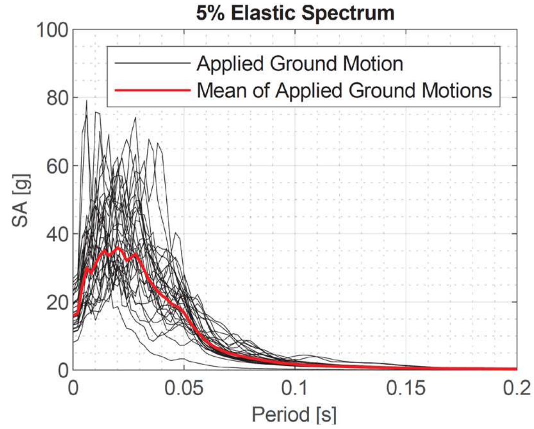

Figure 4. The applied ground motions: pseudo-acceleration elastic response spectra (ζ = 5%).

Table 1. Details of the applied seismic records.

Speci-men	Earthquake Name	Year	Station Name
1	Northridge-01	1994	LA - Sepulveda VA Hospital
2	Northridge-01	1994	Northridge - 17645 Saticoy St
3	Northridge-01	1994	Northridge - 17645 Saticoy St
4	Northridge-01	1994	Rinaldi Receiving Sta
5	Northridge-01	1994	Sylmar - Olive View Med FF
6	Kobe_ Japan	1995	Nishi-Akashi
7	Kobe_ Japan	1995	Nishi-Akashi
8	Chi-Chi_ Taiwan	1999	CHY101
9	Friuli_ Italy-01	1976	Tolmezzo
10	Duzce_ Turkey	1999	Bolu
11	Manjil_ Iran	1990	Abbar
12	Imperial Valley-06	1979	Delta
13	Hector Mine	1999	Hector
14	Nahanni_ Canada	1985	Site 1
15	Nahanni_ Canada	1985	Site 1
17	Darfield_ New Zea-land	2010	Christchurch Cathedral Col-lege
18	Darfield_ New Zea-land	2010	Christchurch Cathedral Col-lege
19	Superstition Hills-02	1987	El Centro Imp. Co. Cent
20	Superstition Hills-02	1987	Parachute Test Site
21	Superstition Hills-02	1987	Poe Road (temp)
22	Superstition Hills-02	1987	Poe Road (temp)
23	Loma Prieta	1989	Capitola
24	Loma Prieta	1989	Gilroy Array #3
27	Cape Mendocino	1992	Cape Mendocino
28	Landers	1992	Coolwater
29	Northridge-01	1994	Beverly Hills - 14145 Mulhol
30	Northridge-01	1994	Beverly Hills - 14145 Mulhol

31	Northridge-01	1994	Canyon Country - W Lost Cany
32	Northridge-01	1994	Canyon Country - W Lost Cany

Tables 2 and 3 summarize the key results of the vertical compression tests on cylinders (bulk material) and wallets, respectively.

2.5 Instrumentation

The URM models were instrumented with piezoelectric accelerometers and laser displacement sensors to capture both in-plane and out-of-plane dynamic response. Accelerometers were placed at the top of the walls, with selected specimens also instrumented at additional locations to capture spatial variation in response. Out-of-plane displacements of the North wall were measured using laser sensors, mounted on an external rigid frame. High-speed video recordings were obtained for all tests to document damage initiation and collapse mechanisms.

Table 2. Summary of the uniaxial compression test results.

	Elastic modulus [MPa]	**Shear modulus [MPa]**	**Poisson ratio [-]**	**Compressive strength [MPa]**
Mean	3989.0	1647.3	0.21	8.1
CoV	0.068	0.068	0.140	0.054

Table 3. Summary of the vertical compression test results.

	Elastic modulus [MPa]	**Poisson's ratio [-]**	**Shear modulus [MPa]**	**Compressive strength [MPa]**
Mean	2255.5	0.15	982.1	2.85
CoV	0.32	0.15	0.34	0.06

3 SEISMIC RESPONSE AND FAILURE MECHANISMS

3.1 Overview of Test Outcomes

Out of the 29 reduced-scale URM building models that were tested as virgin specimens under unidirectional seismic excitation, 7 specimens experienced structural failure, corresponding to an observed failure probability of approximately 24%. All remaining specimens sustained varying levels of damage without collapsing. The observed damage patterns and collapse mechanisms were highly consistent across tests, despite the use of different earthquake records.

Failure was predominantly associated with out-of-plane instability of the perimeter walls. In all cases, the East wall, which was blind and laterally restrained by the adjacent walls, remained intact. Damage and collapse were concentrated in the West wall and, in several cases, extended to the North wall. Figure 5 illustrates typical failure modes observed in the tested model buildings. In Fig. 5a, the failure is confined to the West wall of Specimen 1. This failure type included the collapse of the west wall, while the rest of the structure remained intact. Figure 5b depicts the failure mode of Specimen 31, where both the West and North walls failed.

Figure 6 plots the input motion characteristics, as well as the structural response measurements for Specimen 1, which failed in the West wall only. The top left graph shows the time history of the acceleration trace of the input motion applied to Specimen 1. The top right graph depicts the 5% elastic spectrum. The bottom left graph depicts the laser measurements for lasers L1, L3, and L4, while the bottom right graph displays the accelerometer measurements for accelerometers I1 and O1. The figure also shows the detachment of sensor O1 during testing. More details on the experimental results can be found in Elmorsy (2025) and Elmorsy et al. (2026b).

3.2 Record-to-Record Variability

Despite the geometric and material uniformity of the specimens, significant variability in seismic response was observed across the test series. This variability was primarily attributed to differences in ground motion characteristics, including spectral shape and energy content. The use of a large number of virgin specimens enabled direct observation of record-to-record variability, which is often difficult to capture in experimental campaigns due to cost and logistical constraints.

3.3 Implications for Numerical Modeling

Experimental observations have direct implications for the numerical modeling of URM structures. The dominance of out-of-plane wall mechanisms highlights the importance of accurately modeling wall-to-wall interaction, boundary conditions, and rocking or sliding response. Furthermore, the observed sensitivity to record-to-record variability emphasizes the limitations of deterministic analyses based on single ground motions.

The dataset generated by this experimental campaign provides a valuable benchmark for validating system-level assumptions, commonly adopted in finite element and discrete element models, particularly regarding stiffness degradation, energy dissipation, and failure criteria.

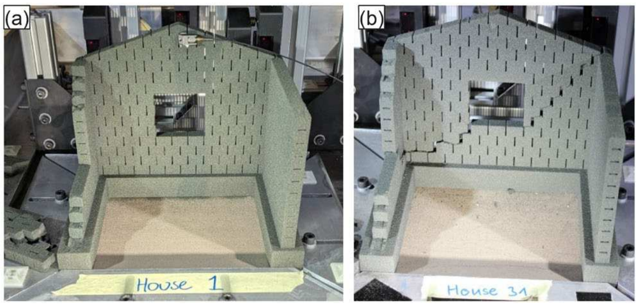

Figure 5. Typical failure modes observed in the tested model buildings: (a) West wall failure only (Specimen 1); and (b) West and North wall failure (Specimen 31).

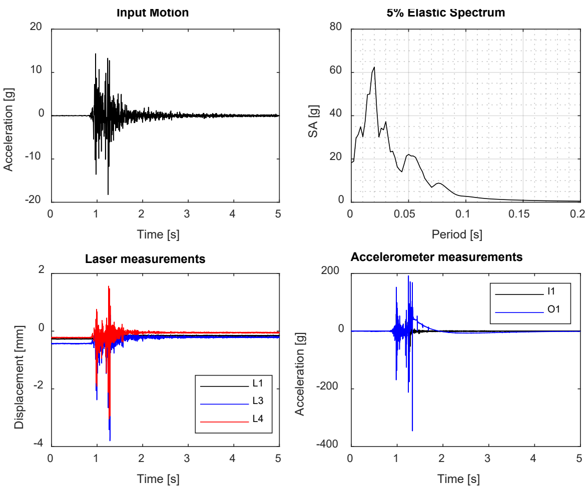

Figure 6. Example of extracted data for Specimen 1 at the model scale, which failed in the West wall only.

4 CONCLUSIONS

This study presented a centrifuge-based experimental investigation of the seismic behavior of URM structures using sand-based additive manufacturing. A series of 29 identical reduced-scale URM building models were fabricated through binder jet 3D-printing and tested as virgin specimens under unidirectional seismic excitation. The experimental campaign combined material-level and component-level characterization with system-level centrifuge shake table tests, enabling a comprehensive evaluation of URM seismic response.

The results demonstrated that the adopted physical modeling strategy successfully reproduces key seismic failure mechanisms observed in URM structures. Damage and collapse were consistently governed by out-of-plane instability of perimeter walls, while the opaque East wall remained stable in all tests. Failure initiation was typically associated with bed-joint opening near the base of the walls, followed by rapid loss of stability once critical displacement thresholds were exceeded. These mechanisms are in good qualitative agreement with observations from full-scale testing and post-earthquake reconnaissance.

Despite the geometric and material uniformity of the specimens, significant record-to-record variability was observed in both response and failure occurrence. The use of a large number of virgin specimens enabled capturing this variability, which is often neglected in experimental studies due to practical limitations. From a modeling perspective, the experimental evidence provided by this study is particularly relevant for validating system-level assumptions in finite and discrete element models, including damping formulation, energy dissipation, and collapse criteria. Overall, the results confirm that centrifuge testing combined with sand-based 3D-printing offers a powerful framework for investigating the seismic behavior of URM structures and supporting the development of reliable seismic assessment tools.

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