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Out-of-plane shake-table tests on unreinforced masonry gables

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Abstract. Typical low-rise masonry buildings worldwide commonly feature unreinforced masonry (URM) walls, often paired with various pitched roof configurations supported or finished by masonry gables. These buildings constitute a significant portion of the building stock in several seismic-prone regions, including areas vulnerable to both natural and induced seismicity. Masonry gables in such buildings are frequently associated with high seismic vulnerability, as evidenced by damage observed after past earthquakes. This paper presents key results from an experimental campaign aimed at enhancing the understanding of the seismic out-of-plane response of masonry gables. Incremental full-scale shake-table tests were performed on three densely instrumented URM gables until complete collapse. Within this context, the study systematically investigated the effects of motions applied at the top of the gable, both being linearly amplified as well as amplified and out-of-phase, with respect to the motion applied at the base of the gable. Such differential motions simulate the effect of the gable interaction with three different roof configurations, each exerting a different filtering effect on the seismic motion. The response of the gables to both induced and tectonic earthquakes was considered. All generated experimental data are available for download at <https://doi.org/10.60756/euc-1avy7q49>.

Keywords: Differential input motions, Gable walls, Incremental dynamic shake-table tests, Roof stiffness, Out of plane, Unreinforced Masonry.

Research overview

Low-rise masonry buildings in Europe and worldwide are predominantly characterised by unreinforced masonry (URM) walls paired with various pitched roof systems, often

supported by masonry gables. These structures constitute a significant proportion of the building stock in seismic-prone regions, including areas exposed to both natural seismic hazards and induced seismicity. Among their components, masonry gables are often identified as the most seismically vulnerable components in their out-of-plane (OOP) direction. Post-earthquake damage assessments worldwide provide extensive evidence of this susceptibility, which stems from several factors: their pronounced slenderness, weak connections to the roof structure, and their position at the building apex. This positioning exposes them to amplified seismic excitation compared to the motion at the ground, while they are under minimal vertical overburden loads. Moreover, the interaction between gables and flexible roof diaphragms can further increase vulnerability, as timber roof elements may amplify seismic motion rather than provide effective restraint. Despite the well-documented seismic vulnerability of URM gables, dedicated experimental studies [1,2] on their seismic response remain limited in the literature. Most available insights are derived from tests on walls with rectangular geometries [3–7], leaving a gap in the understanding of the specific behaviour of gables under seismic loading. To address this gap, this work presents experiments on the dynamic seismic behaviour of full-scale URM gables tested until complete collapse. All generated experimental data from the experimental campaign is available for download at <https://doi.org/10.60756/euc-1avy7q49>.

The tested specimens consisted of identical full-scale URM gable walls, triangular in shape, with a base length of 6 m and a height of 3 m (Fig. 1), and were built on a composite steel-concrete foundation. The gables were built using solid clay bricks, with average dimensions of 230 x 105 x 55 mm, resulting in a wall thickness of 105 mm. Each gable was built in 45 layers of bricks, with 10-mm-thick mortar joints. These bricks exhibited a mean compressive strength of 42.57 MPa, while the mortar showed a mean compressive strength of 0.68 MPa and a flexural strength of 0.20 MPa. Five joist pockets were incorporated to accommodate five timber beams, with a cross-section of 100 x 200 mm. These beams were used to transfer the vertical load representative of the roof diaphragm weight, as well as to apply lateral loads along the height of the specimen. The timber-to-masonry connections relied solely on friction.

The incremental dynamic shake-table tests on full-scale masonry gables were conducted at the EUCENTRE laboratory in Pavia (Italy), using the 9D LAB facility. This advanced seismic testing system features a dual shake-table configuration, including a top and bottom table capable of applying differential input motions. While the 9D LAB in-plan dimensions (i.e., 4.8 x 4.8 m) allowed for testing a full-scale masonry gable, it could not accommodate an entire roof diaphragm structure. As a result, the influence of the roof stiffness on the seismic OOP response of the gables was accounted for by varying the input motion imposed to the top table. In particular, within the same experimental campaign, three different configurations for the roof structure were considered: (i) Gable1-STIFF, representing a rigid roof diaphragm, where the top shake table replicated the motion of the bottom table; (ii) Gable2-SEMIFLEX, representing an intermediate case, where the top motion was linearly amplified relative to the base motion; and (iii) Gable3-FLEX, simulating a flexible roof leading to amplification and phase shift at the gable top.

The experimental setup consisted of a dual shake-table configuration, comprising a top and bottom table capable of applying differential input motions (Fig. 1). A loading frame, assembled using tailored steel profiles, was employed to transmit accelerations along the gable height via five horizontal loading arms that were hinged to the frame. Timber beams were screwed to the steel arms to replicate the timber joists commonly found in real roof structures. The loading frame was hinged at both the bottom and top shake tables to avoid introducing additional OOP stiffness and strength to the gable specimens, whose foundations were fixed to the bottom shake table using steel bolts. Vertical pre-compression was applied to the gable specimens by pulling down the horizontal steel arms by means of steel bars in series with a system of five springs, one for each loading arm. These were pre-compressed to apply a vertical load of 4.5 kN through each timber beam. A total vertical load of 22.5 kN was applied to the gable, simulating half the weight of a timber roof, consistent with the geometry of the tested gable specimen.

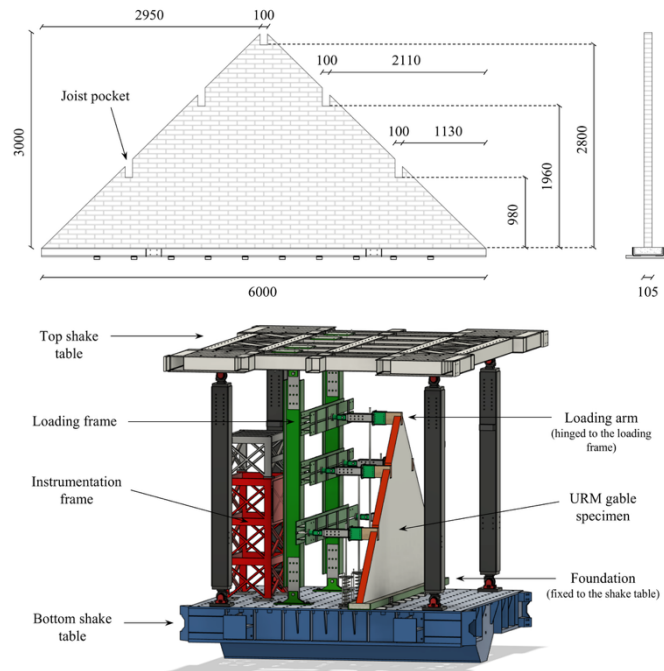


Fig. 1. Geometry of the masonry gable in units of mm (top) and three-dimensional view of the shake-table testing setup (bottom).

The applied input motions considered two alternative scenarios, representative of both induced (FM1) and tectonic (FM2) seismicity. For the induced scenario, numerical analyses were conducted on the finite element model of a typical URM building from the Groningen region of The Netherlands. For the tectonic seismicity scenario,

recordings from the 2016 Central Italy earthquake, obtained from a monitored masonry building at the attic floor level, were used. In this case, the gable-roof interaction was modelled using a representative elastic single-degree-of-freedom system. Further details about the input signal selection can be found in [8]. Each gable specimen was submitted to an incremental dynamic test (IDT) using both FM1 and FM2 input signals until their complete collapse.

Under this testing sequence, all three tested gables exhibited a one-way bending failure mechanism, with complete collapse preceded by a three-body rocking mechanism about hinges formed by two horizontal flexural cracks spanning the length of the gable at the locations of the two sets of timber joists (Fig. 2). The seismic capacity of the gables and the influence of roof flexibility on their seismic capacity is evident from the incremental dynamic testing curves provided for Gable1-STIFF and Gable3-FLEX in Fig. 2. These curves are obtained by plotting *PBA* (peak bottom table acceleration) of each test against the corresponding maximum displacement of the gable (i.e., $\max(d_{ctrl})$) at each level of acceleration input. The influence of roof flexibility on the seismic response of URM gables is evident when comparing the two capacity curves: Gable3-FLEX exhibits significantly lower seismic capacity and substantially higher flexibility.

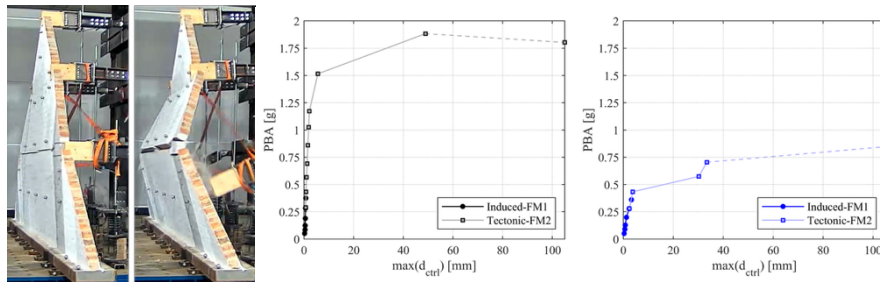


Fig. 2. Failure mechanism (left) and capacity curves of Gable 1-STIFF and Gable3-FLEX (right).

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