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Out-of-plane behavior of two-layered free-standing masonry walls: Analytical solutions and small-scale tests

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ABSTRACT

This study explores the possibility of adopting small-scale models for understanding the behavior of two-layered masonry walls. The units were made of gypsum powder and produced by a 3D printer. The tests were conducted by means of a tilting table, which provided a first order seismic analysis leading to the discovery of the minimum value of the horizontal/vertical acceleration ratio that triggers the collapse. In order to conduct a qualitative analysis, a high-speed camera and dedicated software were employed. Beforehand, theoretical predictions were given (expressed by dimensionless parameters) both for the failure domain and failure angle. Experimental tests showed that for various failure mechanisms, different reduction factors should be applied – because of the interference of imperfections. Additionally, at the borders between some failure modes, mixed modes can occur with an unfavorable effect on load capacity. A high-speed camera and software utilization helped to explain the asymmetric frame-like failure mechanism occurrence which could not have been predicted theoretically. As a final result, a new diagram with failure domains and a set of governing equations along with reduction factors were delivered.

1. Introduction

Multilayered walls can consist either of two or three layers (also called leaves or wythes). If there are three of them, external layers are called cladding or skin and the internal one is called a nucleus or core. The core is usually of lower quality (uneven spacing, size, and shape of blocks) and may contain a significant ratio of voids. The variety of blocks used for external leaves is vast as well – both in terms of shape and material. The diversity of used mortars is another factor. Mortars, in the past, were generally much weaker than their modern counterparts – mainly because they were based on lime binders. The next feature is the presence and spacing of so-called through-stones – the blocks which pass through more than one leaf. The spacing of through-stones may differ in horizontal and vertical directions; they may be spaced evenly or scattered randomly. If one desires to deepen their knowledge in this field, there are numerous positions covering typology and specificity of multilayered historical walls – [1–3].

Multilayered walls rarely occur (besides fortification, historical ruins, municipal or retaining walls) as free-standing isolated elements (Fig. 1). However, in order to understand their behavior and role in more complex structures, their performance as generic elements has to be correctly understood and quantified. Out-of-plane behavior of multilayered walls has so far been tested by means of different experimental techniques; however, contrary to one-layered dry or mortared walls, the database is still quite limited. The first experimental tests were executed by Ceradini [4]. He conducted small-scale tilting tests on a type of wall known as *opus quadratum* (from Ancient Rome) – regular cuboid stone blocks stacked without mortar. His analysis was conducted on both two-layered and three-layered walls, with the variable being the number of through-stones. In his work [5], Mazzon investigated three-layered stone walls consisting of regular cladding and rubble infill by means of a shaking table. A shaking table was also employed by Magenes et al. [6] to conduct an experimental campaign in order to understand the behavior of undressed double-leaf stone masonry and its performance within two-story buildings. Similar research is described in [7]. The next category is so-called airbag tests, where out-of-plane loading is applied uniformly on the wall's surface by means of pressure constantly increased in the nylon bags. Regular multilayered brick walls with good mortar bonding were tested in [8]. Airbags were successfully applied by Ferreira et al. both in laboratory [9] and in-situ [10] campaigns to test traditional multilayered stone walls. In their work [9], the authors treated the number, spacing, and relative area of through-stones as variables. The distance from the base to the first through-stone was considered as well and it turned out to be an important factor, both

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Fig. 1. Free-standing two-layered wall in rural Poland, damaged through the separation of layers.

from the qualitative and quantitative point of view. A notable outcome was that cracks occurred only in the mortar joints. In the same experimental campaign, specimens were also tested by means of a horizontal line-load at the top. The line-load is used in-situ as well, and during the experimental tests described in [11], both unreinforced and reinforced multilayered panels were tested. The authors pointed out that a gradual degradation of interlocking between the layers was the decisive factor causing the collapse of the masonry, which resulted both in decreasing the wall's monolithicity and triggering an adverse reaction of the infill material constituting the core.

Besides experimental campaigns, some numerical analyses were conducted to address this problem. De Felice [12], by means of distinct element software, reproduced the tests done by Ceradini [4], and subsequently switched to irregular cross-sections typical for Italy. He reported substantial differences between quasi-static and dynamic response in case of two-layered walls with no interlocking. Furthermore, dynamic analyses have clearly shown that the walls with interlocking have brought about a capacity curve lower than the rigid body rocking curve. Isfeld and Shrive [13] analyzed the decaying multilayered walls of Prince of Wales Fort with the discrete element method, basing experiments on a detailed in-situ survey.

Analytical solutions developed to assess specifically the out-of-plane capacity of multilayered walls are very limited. Mostly in Italy, methods were developed based on identifying local mechanisms (in form of macroblocks) and applying to them the rules of limit analysis, just to mention: [14,15,3]. These methods are applied both to monolithic and multilayered masonry buildings. There is huge potential in adopting closed solutions developed for one-layered dry walls in different configurations – if correctly rearranged and experimentally validated they could provide a great assessment tool for multilayered walls. One of the latest and most plausible proposals, revealing a close agreement with experimental tests is described in [16]. Similar work is presented in [17], where special emphasis was placed on interlocking between orthogonal walls. Both in [16,17] a tilting table and small-scale stone blocks were used to validate the analytical predictions. A similar approach was applied to dry masonry structures in work [18]. In work [19], some analytical and experimental considerations are provided for dry block masonry as well (also in scale).

This article aims to explore the failure scheme and out-of-plane load capacity of two-layered walls as a function of the cross-section. It is realized both through analytical predictions and small-scale experimental tests. High-speed cameras and dedicated post-processing software are involved as well. The results of the research give more insight into the understanding of the importance of through-stones for the monolithic behavior of walls. Specifically, the transition of failure modes is investigated (effect of modes' coupling), which is associated with reduction factors. Also, the assumption about treating masonry as a set of rigid bodies is addressed qualitatively and quantitatively. The final results should increase the ability to assess existing structures (in engineering practice) and point out critical features of cross-sections. Furthermore, the next step of introducing modern methods into historic masonry testing is taken, as well as exploring the usefulness of 3D printing and high-speed cameras.

2. Methodology

Analytical calculations are based on the following assumptions postulated by Heyman [20]: (1) masonry blocks are infinitely rigid, (2) blocks have infinite compression strength, (3) masonry has zero tensile strength, (4) blocks are rough – there is a non-zero value of friction coefficient between them. The first point seems quite justified as under typical loading the strains in masonry are relatively low and usually associated with mortar, not units. The second assumption is almost always true as the stress level in masonry is usually quite low and it is very unlikely that compression can cause the failure of masonry wall; however, it might be an issue in case of heavy loaded masonry structures in combination with the creep phenomenon, [21]. Zero tensile strength does not mean that masonry is not able to work in tension, as it is still capable of doing that through mechanical interlocking of units and the presence of friction. It is more connected with the mortar, which is fundamentally very weak in historical structures, or has already been displaced or deteriorated by environmental agents and, even if present, is very hard to establish its mechanical properties. Hence, the assumption about no contribution from the mortar to the capacity of masonry is fairly justified and furthermore stands on the conservative side as well.

Experimental tests are run by means of a tilting table on small-scale models. A tilting table test is a quasi-static test and might be considered as a first order seismic analysis as the angle at the collapse is the ratio between the horizontal and vertical acceleration. During the experiment, the angle is constantly increased which causes the drop in vertical acceleration ($g \cdot cos\alpha$) and an increase in horizontal acceleration ($g \cdot sin\alpha$), where g is the Earth's gravitation and α is the measured angle. The tilting test was chosen as it reassures quite correctly the nature of seismic loading – evenly distributed horizontal body loading, while the small-scale models provide the opportunity to run numerous series of tests with reasonable time, work, and cost effort. Moreover, what is crucial is that the change of the scale does not imply any inherent scaling effects as the considerations are based on stability. Besides the quantitative information in the form of an angle, an important piece of qualitative information is acquired, namely the failure scheme which varies with the blocks' arrangement and presence or spacing of through-stones. However, as at the moment of the collapse, the blocks undergo quite significant accelerations, the failure scheme is difficult to identify with the naked eye or even by means of an ordinary video-camera. Therefore, to overcome this issue, a high speed camera as well as special software is utilized. Having both theoretical and experimental results, conclusions can be made and failure domains established. The