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Investigation of the Shear-Compression-Load Bearing Behavior of Unreinforced Brick Masonry Using the Unit-Cell-Method

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ABSTRACT

Unreinforced brick masonry is a characteristic feature of historic buildings in Germany and Europe. Despite its widespread use, knowledge of its shear-compression performance under static and cyclic loading, particularly in relation to earthquake exposure, has stagnated for decades. A recent research project at the Technical University of Munich focuses on the shear-compression performance of traditional small-format brick masonry and the influence of different masonry thicknesses and the use of vertically perforated bricks, to fill this essential gap in knowledge.

To investigate the shear-compression behavior of unreinforced masonry (URM) in more detail in a cost- and space-saving manner the "unit-cell-method" was developed. In contrast to full-scale shear wall tests, the unit-cell-method allows for a cost-effective and flexible investigation of various parameters. For this purpose, small test specimens are tested for their shear-compression load-bearing behavior. Different test configurations enable the simulation of the load and stress state in the wall head, base or center under monodirectional static and cyclic loading of a URM shear wall.

This paper presents the innovative, less cost and space intensive unit-cell-method and provides an outlook on planned test series. The new findings will lead to a more in-depth understanding of the shear-compression performance of URM masonry through systematic investigations and the development of empirical models. This will not only contribute to the preservation and restoration of architectural heritage, but also improve the structural integrity and safety of existing buildings.

KEYWORDS

biaxial-load, brick, brick masonry, cyclic load, earthquake, shear-compression load, shear load behavior, small-format brick masonry, unreinforced masonry, unit cell, unit-cell-method

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INTRODUCTION

Until today, the European design concept for URM under shear-compression stress is based on the model by Mann and Mueller [1] from the 1970s. Although this model has been further developed and, in particular, adapted for masonry made of large-format blocks, there are still open questions and uncertainties in understanding the shear-compression-load-bearing behavior of URM. Therefore, the design is carried out under quite conservative assumptions, which underestimate the actual load-bearing capacity of masonry. For the construction of new buildings, this means an uneconomical design with a significant safety margin. In the case of the static reassessment of existing buildings, however, this fact has even more far-reaching consequences, potentially leading to the imminent demolition of buildings that actually have sufficient load reserves. Before structural measures can be taken on existing buildings, they must be verified according to currently applicable standards with new, usually higher loads. In addition, the new Eurocode 8 is about to be introduced in Germany, which foresees an approach for higher loads caused by earthquakes. The static reassessment under the approach of higher loads in combination with the underestimation of the load-bearing capacity of existing masonry structures suggests that a large number of existing buildings will have an insufficient load-bearing capacity and will have to be replaced by new buildings.

To prevent the demolition of this large number of historical buildings, new assessment methods for existing masonry structures are required. Until today, there is uncertainty in understanding the shear-compression-load-bearing behavior of URM made of small-format bricks. This requires further experimental investigation. However, the common shear wall tests are space- and cost-intensive. For this reason, the unit-cell-method was applied to masonry structures under shear-compression-loads by Scheufler and Zilch [2] and later extended by Eisinger and Fischer [3] at the Technical University of Munich (TUM). This test method allows small specimens to be tested under realistic unidirectional or cyclic shear-compression loading and therefore allows for a more precise investigation of the various failure mechanisms of URM walls under panel shear at comparatively low costs. To fully explore various influencing parameters on the shear-compression-load-bearing behavior, additional tests with variations in the masonry bond, type of bricks, and masonry thickness will be expanded in the future. This contribution provides an insight into the used test method and the planned test series at TUM.

STATE OF THE ART

The first significant investigations into the shear-load-bearing behavior of masonry were conducted in 1965 at the University of Edinburgh by Hendry and Murthy [4]. Results from racking tests (see Fig. 1 (a)) on walls made of small-format model bricks were compared with tests on full-scale, URM shear walls. Sinha and Hendry [5, 6] later additionally investigated the influence of the masonry bond on the load-bearing capacity and shear behavior of walls with and without openings. In 1980, Samarasinghe [7] examined the influence of different inclination angles of the bed joint on the shear behavior. By conducting these experiments on model masonry, the experimental effort was significantly reduced. However, the authors recognized that scale effects might influence the test results if certain boundary conditions are not met (e.g. scaling of bed joints) [7]. Within the studies, no further evaluation of size effects was conducted.

At the University of Newcastle, in the 1980s Page [8, 9] conducted similar tests on square masonry specimens, as shown in Fig. 1 (b). The test specimens were made of small-format bricks with halved brick dimensions and with different orientations of the mortar joints to also investigate the influence of the angle between the bed joint and the load application on the shear capacity. In [8] the author detected a positive influence of the multiaxial stress state on the load-bearing capacity of masonry. The focus was particularly on deformation measurements, with which Dhanasekar et al. [10] later developed a modified failure envelope.

At the Technical University of Darmstadt, investigations on the shear-load-bearing behavior of masonry made of small-format bricks were also carried out in the 1970s (cf. [1]). The test specimens were also made of small-format bricks with halved cross-sectional dimensions to reduce the dimensions and the testing effort. The test setup allowed for controlled, biaxial load application via toothed strips on the top and bottom as well as via transversely laid individual bricks on the left and right edges of the test specimen (see Fig. 1 (c)). Based on these tests, Mann and Mueller [1] developed a design model with four failure modes in 1978, which still forms the basis of the shear design of masonry according to Eurocode 6. In 1990, Dialer [11] conducted his own shear tests on model masonry at TUM and extended the model of Mann and Mueller [1]. The influence of relevant parameters on the validity of model tests was again pointed out. In particular, the challenge of not being able to reduce the bed joints to the same extent as the bricks resulted in a compressive strength of the masonry that was approximately 10% lower [11]. Dialer [11] emphasizes the importance of representing all necessary material parameters and boundary conditions as accurately as possible.

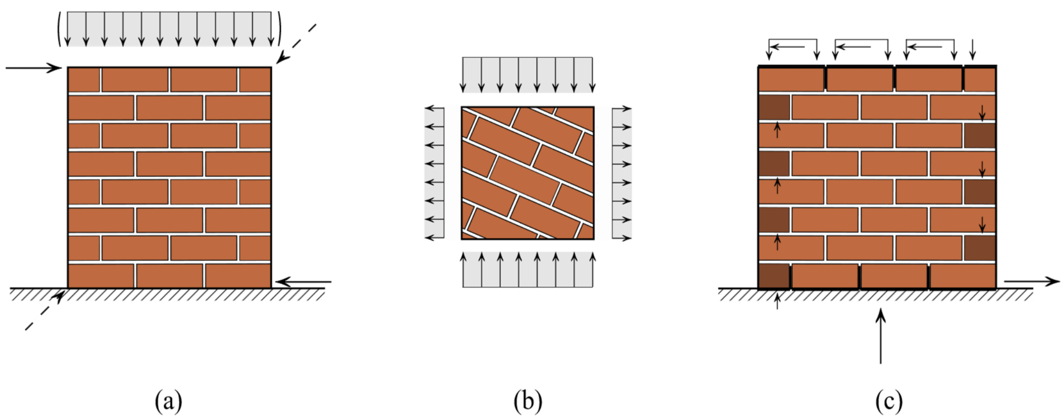


Figure 1: Test concepts for shear tests following [11] and [1]

UNIT CELL METHOD

Test Concept

Full-scale shear wall tests are both extremely cost- and space-intensive. For this reason, shear tests on reduced-scale model masonry panels have been conducted in the past. However, these model tests can lead to unwanted scale effects if specific parameters are not maintained. With this in mind, Scheufler and Zilch [2] developed an innovative test setup for investigating small masonry specimens, called unit cells. Each unit cell represents a theoretically cut-out, regularly recurring area of a shear wall, as shown in Fig. 2. Testing these unit cells allows for a realistic investigation of the shear-load-bearing behavior of a masonry wall under unidirectional and cyclic loading, without the experimental effort of testing a full-scale shear wall and without the risk of scale effects. The main focus of the investigations in [2] was on masonry made of clay blocks with thin bed mortar and the differentiation of the various failure mechanisms depending on normal stresses.

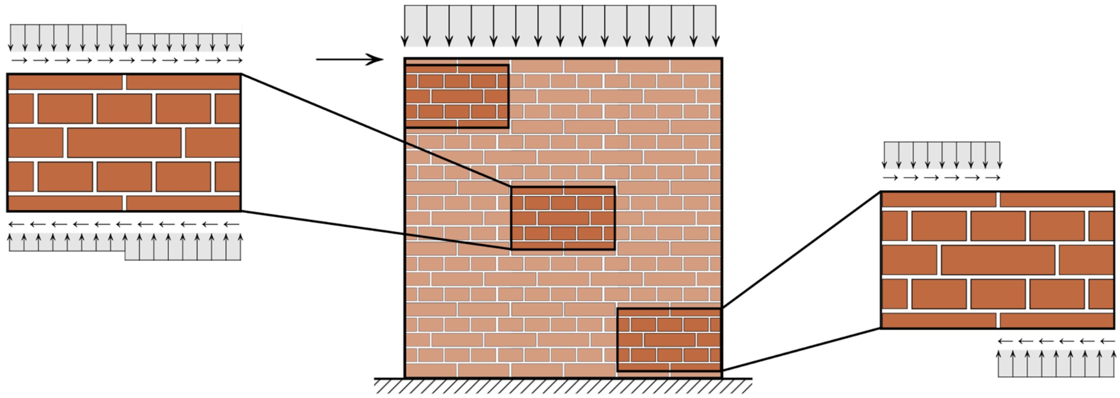


Figure 2: Concept of the unit-cell-method

Eisinger and Fischer [2] later improved and extended the unit-cell-method to other brick formats, conducting investigations in recent years on the suitability of the unit-cell-method for masonry made of small-format bricks. Initially, only masonry specimens with the same dimensions and bond type but different brick-mortar combinations were investigated. New as well as reclaimed solid bricks were used, which were laid into unit cells in an English cross-bond with two different lime mortar mixtures. Due to the already small brick format, the first and last course of the unit cell were not halved but are nevertheless referred to as unit cells in the following text. The conducted unit cell tests were then compared with full-scale shear wall tests, where a very good agreement was found [2]. Building on these results, the unit-cell test setup has been further developed to investigate the influence of different wall thicknesses and bond types, as well as vertical perforation of the bricks on the shear load-bearing behavior of unreinforced masonry made of small-format bricks. These investigations are supported by advanced metrology such as digital image correlation.

Test Setup

The unit cell test setup consists of a prestressed reinforced concrete frame in which six vertically acting and three horizontally acting hydraulic cylinders are mounted (see Fig. 3). Two vertically and one horizontally acting hydraulic cylinder each control a load plate. This allows the lower left and the two upper load plates to be controlled, while the lower right load plate serves as a fixed support. Each load plate introduces the load condition into the unit cell according to a defined control. The head joints of the masonry are exactly at the joints of the load plates, so that the bricks are loaded individually. A small layer of gypsum provides direct load transfer from the profiled load plate to the bricks.

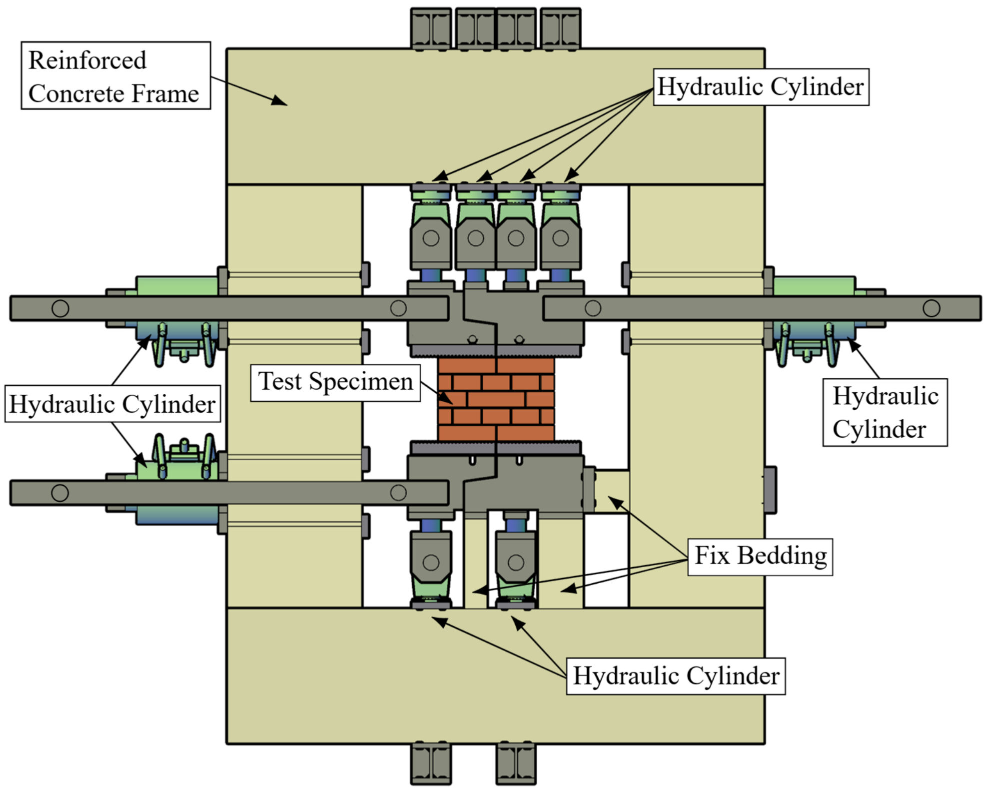


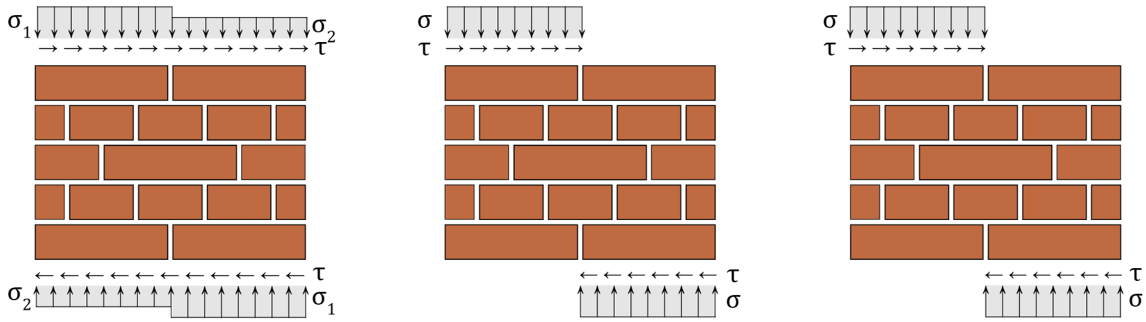
Figure 3: Unit-cell test setup (following [2])

The test setup is usually operated with three different test procedure, as shown in Fig. 4, allowing various load scenarios and test conditions to be implemented flexibly. The different control configurations enable the loading of the unit cells under realistic stress conditions in the various design-relevant wall areas, wall center, wall base and wall top (see Fig. 2).

Test procedure A, ”Mann-Mueller state”, generates a stress condition corresponding to the stress condition in the middle of a wall under shear-compression stress. First, a predetermined, uniform normal stress is applied. After reaching the specified normal stress, the shear stress and thus the inclination angle of the resultant force, which runs through the center of the test specimen, are increased until failure. As the horizontal load increases, the vertical cylinders counteract the resulting moment. This load distribution creates a stress condition on the individual brick in the wall center, as known from [1].

Test procedure B, ”shear-compression test”, simulates a stress condition as it occurs at the wall base or top under shear-compression stress. The shear and normal stresses are increased under a constant inclination angle of the resultant force until the unit cell fails. The load is applied only through the upper left load plate, while the other two controllable load plates remain unloaded, similar to what is expected at the wall base or top of a shear wall.

In contrast to test procedures A and B, which are unidirectional tests, test procedure C performs a cyclical load sequence. In test procedure C, the stress condition at the wall top or base of a shear wall is simulated similarly to test procedure B. The loading also occurs under a constant inclination angle of the resultant force, but the normal and shear stresses are not continuously increased until failure. The loading in this test procedure is carried out in three loading and unloading cycles within a load regime before the next higher load regime is approached until failure occurs.



Test procedure A

Test procedure B

Test procedure C

Figure 4: Test procedures of the unit-cell test setup (cf. [2])

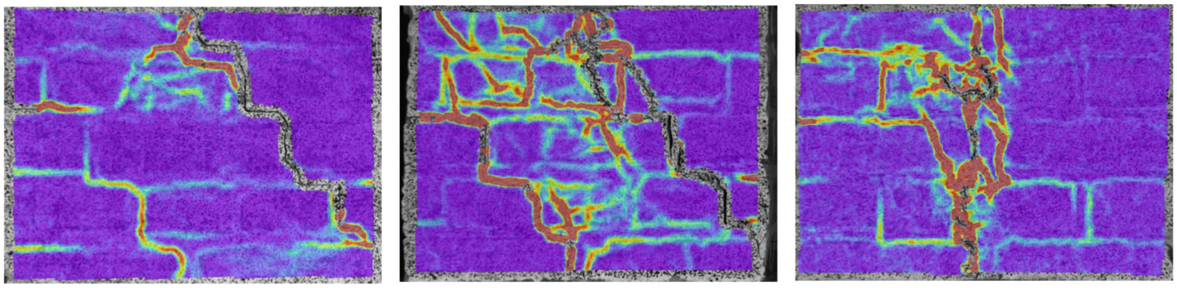
Measurements

To capture crack formation and fracture patterns, a close-range photogrammetry system based on digital image correlation (DIC) is used. In this process, 2D or 3D coordinates are determined from image series using stochastic pattern recognition at different load states, and the respective displacements and distortions are calculated by comparing them with reference images of the unloaded state. Close-range photogrammetry systems using DIC consist of the recording unit (one or more industrial system cameras), the measurement and storage unit, and an evaluation system [12]. For the evaluation, the commercial software Istra4D from the system manufacturer Dantec Dynamics A/S is used.

Before the tests, the surfaces of the specimens are prepared with a flat stochastic black-and-white pattern, and individual retrospective measurement points are applied. During the test, images of the measurement field of the unloaded and successively loaded specimen are taken with two high-resolution cameras (optical sensors) at a measurement frequency of 0.2 Hz.

In post-processing, the initial image of the unloaded specimen is divided into a multitude of small facets with application-dependent size and spacing. Based on the characteristic gray value distribution, the corresponding patterns of the facets of the further load states can be identified, and the 3D coordinates can be calculated. Using a strain tensor, which represents the relative displacements between the calculated coordinates, the strains in the X, Y and Z directions as well as the principal and secondary deformations are calculated.

The graphical representation of these strains as well as the principal and secondary deformations enables the detection of the crack origin and progression throughout the entire test configuration. This allows for a detailed analysis of the various failure mechanisms of masonry under panel shear. If a stepped strain pattern with cracks running exclusively in the joints is observed, as shown in Fig. 5 (a), it can be concluded that friction failure has occurred. If cracks run in both the head and bed joints and additionally through bricks starting from the head joints, as can be seen in Fig. 5 (b), this indicates a mixed failure of friction and tensile failure. Cracks exclusively in the head joints and from there through bricks indicate tensile failure, while vertically running cracks, as shown in Fig. 5 (c), suggest tension failure.



(a) (b) (c)

Figure 5: Different failure patterns of unit-cell samples captured with DIC

In addition to close-range photogrammetry, other measurement technology is also used in the tests. Load cells and displacement transducers are placed on each of the nine hydraulic cylinders of the unit cell test setup. These measure the respective acting force and the relative displacement of each individual cylinder throughout the entire test. The measurement data from the load cells and displacement transducers are recorded and stored, allowing for the determination of, for example, the total failure load, the inclination angle of the resultant force, and the maximum displacement in the vertical and horizontal directions.

PREVIEW

The good agreement of the results from unit-cell tests with results from shear wall tests has already been established by [3]. These investigations focused on the influence of different brick-mortar combinations on the shear wall resistance of URM. In these tests, the unit-cells were made from two different types of solid bricks and two different types of historical lime mortar, while the dimensions and masonry bond remained the same. To fully cover the application of historical masonry, solid brick masonry with different wall thicknesses and masonry bonds, as well as masonry made of vertically perforated bricks, is now being investigated using the unit-cell-method. Two test series additionally also consider the eccentric loading from partially supported floors, often found in masonry walls. The test results for selected parameter combinations are verified by shear wall tests.

As part of current investigations, unit cells made of masonry with three different wall thicknesses of 120 mm, 250 mm, and 380 mm are being produced. Unit-cells with a wall thickness of 120 mm are built in a Stretcher bond (see Fig. 6 (a)), while the unit cells with greater wall thickness are built in an English cross-bond (see Fig. 6, (b) and (c)). The test specimens are made of historical lime mortar MG I and small-format solid bricks, which were taken from historical buildings in Germany.

As part of the current research project, the shear-load-bearing behavior of masonry with wall thicknesses of 120 mm and 380 mm under centric, full-surface shear-compression loading is considered, while the shear-load-bearing behavior under centric, full-surface shear-compression-loading of masonry panels with a wall thickness of 250 mm was already investigated in the previous project [3]. Additionally, the unit cells with a wall thickness of 250 mm are subjected to eccentric partial surface loading to more precisely examine the influence on the shear-compression-load-bearing behavior.

t = 120 mm t = 250 mm t = 380 mm

Figure 6: Unit-cells with different masonry thicknesses and masonry bonds

Around the 1950s, vertically perforated bricks were first used to achieve lower thermal conductivity with similarly high load-bearing capacity. For this reason, unit cells made of small-format perforated bricks and historical lime mortar are also being produced. The perforated bricks have the same dimensions as the solid bricks and were manufactured in a historical manner. The unit cells are built with a wall thickness of 250 mm in an English cross-bond, as shown in Fig. 7. The loading of these test specimens is carried out in a first test series under centric, full-surface shear-compression loading and in a second test series under eccentric, partial surface shear-compression loading. This allows for a direct comparison of the shear-load-bearing behavior of masonry panels made of solid bricks and perforated bricks.

Figure 7: Unit-cells made of perforated bricks

Initial unit cell tests have already been conducted with the previously described test specimens and have yielded promising results. As expected, an increase in the overall shear-compression-load-bearing capacity with increasing wall thickness was evident in each test configuration. With the ratio of shear stress to normal stress, the fracture pattern and thus the failure mode of the masonry specimens also changed as expected. In the further course of the project, the described unit cell tests will be completed and evaluated. Subsequently, shear wall tests will be conducted to validate the unit cell tests and establish a practical reference for the unit-cell-method.

CONCLUSION

The unit-cell-method is being further developed to gain more insights into the load-bearing behavior of URM made of small-format bricks with standard mortar joints under shear-compression-stress in the future. For this purpose, further test series with varying masonry thicknesses, bond types, and materials (solid and perforated bricks) are conducted. Full-scale shear wall tests complement these investigations and serve to validate the test results. Precise measurement technology, including load cells, displacement transducers, and DIC, enables the recording of forces, displacements and strains to identify failure mechanisms such as friction, tensile, or compressive failure. The findings aim to optimize the computational verification formats for masonry with the goal of being able to demonstrate the load-bearing capacity of URM shear walls in the static reassessment of existing buildings. By improving the accuracy of structural assessments, this research contributes to the preservation of historic masonry and architectural heritage, ensuring that existing structures can be maintained and adapted for future use.

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