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The compressive strength of vertically perforated clay block masonry predicted by means of a unit-cell type numerical simulation tool taking discrete cracking into account

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HIGHLIGHTS

- Numerical simulation of masonry built up by vertically perforated clay blocks.
- Numerically obtained compressive strengths agree very well with experiments.
- Vertically perforated blocks show failure mechanisms different from solid clay blocks.
- A unit-cell approach with periodic boundary conditions is presented.
- Brittle failure is taken into account by means of the extended finite element method.

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ABSTRACT

Vertically perforated clay blocks with an excellent ratio of load-bearing capacity to thermal properties are highly sophisticated products, which due to their higher complexity require advanced design concepts for a reliable prediction of performance characteristics. Since the contact between blocks strongly influences the compressive strength, it is insufficient to consider single block strengths. To tackle this challenge, our numerical simulation tool is based on a unit-cell approach with periodic boundary conditions, so interaction between blocks can be considered. An extended finite element approach allows for modelling discrete cracks and, thus, brittle failure modes and compressive strengths can be predicted correctly.

1. Introduction

The development of new vertically perforated clay block geometries, either to reduce the effective thermal conductivity or to increase the load carrying capacity, is a highly sophisticated process, which is often driven by the experience of skilled workers and engineers. Such developments require the production of new extrusion tools and subsequent comprehensive test series. As this highly time- and cost intensive procedure inhibits innovation, support through numerical simulation tools for predicting both the effective thermal conductivity as well as the load carrying capacity seems advisable. For predicting the effective thermal conductivity a promising approach has already been proposed by Zukowski and Haese [47]. So far, at least to the authors' knowledge, no attempt has been made to model the load carrying capacity of vertically perforated clay block masonry by means of numerical methods.

However, numerous authors proposed different methods to estimate the load carrying capacity of solid bricks, which can be roughly classified into: numerical [2,21,28,29,39–42], analytical [13,18,23,37,46] and phenomenological methods [17,19,35]. All these proposed methods are mainly useful for the estimation of the load carrying capacity of existing solid brick structures, but are not suitable for the development of new vertically perforated clay block geometries. They all assume, for the case of axial compression, that the main failure mechanism is induced by lateral tension in the brick due to the different lateral deformation behaviour of brick and mortar, first thoroughly investigated by Hilsdorf [23]. For the case of vertically perforated clay blocks this assumption is hardly true. Due to complex geometries and the usual offset of superimposed bricks, they are never in full contact, but rather have a few contact areas between webs. For this reason, failure is mainly induced by transverse tensile stresses in these webs, and

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as such, the contact between clay blocks has a strong influence on the load carrying capacity of the masonry which they build. Therefore, the real stress constraints on a single clay block need to be taken into account as well as the interaction between brick and thin bed mortar.

As therefore the load carrying capacity of a single clay block (experimentally or numerically obtained) does not allow for a suitable estimate on the load carrying capacity of the block in masonry directly, standards recommend the application of reduction coefficients [17] to deduce the load carrying capacity of masonry from single blocks, or to conduct experiments on masonry walls [16]. Experiments are mainly conducted when tested clay blocks cannot be categorized clearly according to EN1996-1-1[17], or when higher results for the load carrying capacity of masonry are expected than could be deduced from applying reduction coefficients. These experiments require masonry specimens with at least a length of two times the length of a single clay block and a height of at least five times the height of a single clay block [16], and are therefore time- and cost consuming.

This has led to the main motivation of this work, namely the development of a numerical simulation tool which is able to accurately predict the load bearing capacity of masonry built up by vertically perforated clay blocks. Based on this motivation, the following objectives of this work can be formulated:

1. The definition of appropriate unit cells for masonry structures and the application of suitable periodic boundary conditions, to ensure computationally efficient simulations despite complex failure mechanisms and brick geometries.
2. The description of brittle failure mechanisms by using the extended finite element method and taking the orthotropic strength behaviour of the brick material into account.
3. Identification of necessary material parameters, as far as possible, by experiments and, additionally, a comprehensive validation of the developed simulation tool by means of compression tests on several different masonry structures with different perforated clay blocks.

Finally, a far better prediction accuracy of the load carrying capacity of masonry structures compared to the prediction based on single brick compression tests should be provided.

In the following section, Section 2, the numerical simulation tool is introduced, while in Section 3 the experiments for the validation of the numerical simulation tool are presented. In Section 4, results from both experiments and numerical simulations are presented and compared. Finally, a short summary and concluding remarks are given in Section 5.

2. Numerical simulation tool

2.1. Unit cell and formulation of periodic boundary conditions

The repetitive arrangement of bricks in masonry motivates the application of the unit cell method (Suquet [45]) with periodic boundary conditions for the estimation of the load carrying capacity. Thereby, the actual strain field within masonry can be reproduced with reasonable computational effort. The unit cell method has been successfully used for modelling masonry by various authors as a homogenization technique for limit analysis (see e.g. [2,28,33,38,41,46]) for solid brick units. To the authors knowledge, the method has not yet been applied for the estimation of the load carrying capacity of vertically perforated clay blocks. In fact, very few publications on the estimation of effective elasticity parameters or effective strength exist for vertically perforated clay blocks, possibly because of the combination of their complex geometries with an extremely brittle failure behaviour, making the development of prediction tools a challenging task. A vertically perforated clay block has been modelled by Moradabadi et al.[39], but with the webs being exactly one above the other, this rather academic example is not applicable for the estimation of the load carrying capacity of masonry walls built on construction sites. Hannawald and Brameshuber [22] proposed an approach for the prediction of the elastic response of vertically perforated clay blocks, though neglecting the influence of bed joints as well as the exact contact area, and thus, stress transfer between clay blocks.

These two restrictions may be overcome by using the unit cell method and the distinct modelling of the bed joints. An illustrative unit cell used in this work is depicted in Fig. 1, and the surface, edge, as well as the vertex node designations are defined in Fig. 2. Due to the application of periodic boundary conditions it is necessary that the upper and lower layers have the same mesh geometry in x-and y-direction (top and bottom surface, see Fig. 2), while different overlap conditions may be prescribed via the middle layer.

On the southern and northern surface, as defined in Fig. 2, no prescriptions are made regarding boundary conditions of the displacement vectors, as the corresponding traction forces on these surfaces are equal to zero. For the remaining surfaces, periodic boundary conditions are applied.

Concerning the unit cell equations to be prescribed on the numerical model, the overall formulations on the surfaces *Top, Bottom, East* and *West* as depicted in Fig. 2 may be written as follows:

$$\mathbf{u}_s(\mathbf{x}) = \langle\varepsilon\rangle\mathbf{x} + \mathbf{u}_{s'}(\mathbf{x}), \tag{1}$$

where $\mathbf{u}$ denotes the displacement vector on a surface s and its corresponding opposite surface s', $\mathbf{x}$ being the position vector and $\langle\varepsilon\rangle$ the effective strain in the unit cell, defined as:

$$\langle\varepsilon\rangle = \varepsilon(\mathbf{x}) - \dot{\varepsilon}(\mathbf{x}) = \frac{1}{V}\int_V \varepsilon \, dV, \tag{2}$$

where $\varepsilon(\mathbf{x})$ denotes the actual strains within the unit cell, and $\dot{\varepsilon}(\mathbf{x})$ the local fluctuations, which have to vanish on the overall volume for sufficiently large unit cells (Böhm [8]):

$$\langle\dot{\varepsilon}\rangle = \frac{1}{V}\int_V \dot{\varepsilon}(\mathbf{x}) \, dV = 0 \tag{3}$$

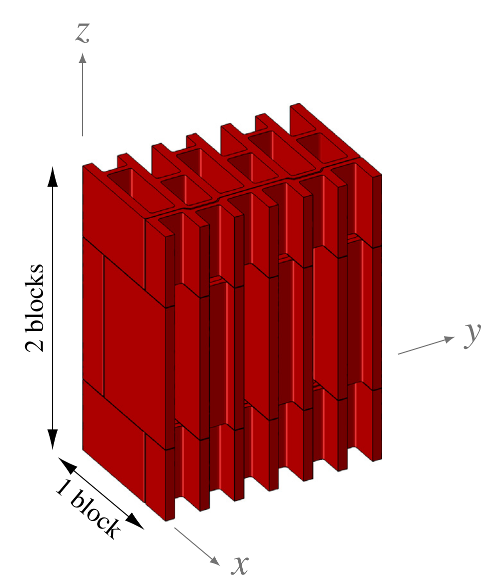

Fig. 1. Illustrative unit cell for running bond masonry with repetitive structure in x- and z-directions.