Partial safety factors for earth block masonry

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SUMMARY:

In the beginning of the 1980s earth building has undergone a renaissance, which nowadays leads to an increasing use of load-bearing earth constructions and in particular, earth block masonry. At present, there are no common structural standards according to the semi-probabilistic design concept, which is the state-of-the-art in European standards. A solid database is needed for the determination of the partial safety factor on the resistance side. Therefore, compressive strength tests were carried out with two types of earth blocks and two types of prefabricated earth mortar. The evaluation showed that the variation of the compressive strength was remarkably less than expected, which seems to indicate high quality standards of the components earth block and mortar with regard to industrial production.

On the basis of these results and together with the reliability method, a partial safety factor for earth block masonry subjected to compression was determined. The main aim of the research was the development of a first valid database for material parameters of earth block masonry with particular regard to statistical characteristics. The results showed that a common calculation method for earth block masonry based on partial safety factors following the valid masonry construction standard is feasible.

1. INTRODUCTION

The knowledge on the material properties and failure mechanisms of earth block masonry is limited and scattered when compared to the advances in research on conventional masonry (stone and brick masonry). Earth block masonry consists of earth blocks and mortar, usually an earth mortar. Nowadays earth blocks can have various forms and sizes with or without hollows. The manufacture of earth block masonry usually follows the same principles as those used for conventional masonry. Although earth block is a widely utilised building material since prehistoric times, it also represents a type of masonry block that yields the lowest strength values. The scatter of mechanical property values in the literature as shown in [1] can be large. This scatter is not only due to factors such as workmanship and weathering, but also to different testing procedures, for instance in the derivation of Young’s modulus.

At the moment, there is no valid European standard or guideline for the design of earth block masonry. The introduction of DIN 18945 [2] and DIN 18946[3] as product standards for earth blocks respectively earth mortar in 2013 in Germany can be used as basis for the development of a semi-probabilistic design method based on partial safety factors. The semi-probabilistic design method or limit-state design is state-of-the-art in structural design and underlies all European structural design standards. Historically the designs of earth block masonry and conventional masonry were closely linked due to similar load bearing behaviour, failure mechanisms and workmanship. An adaption of future design of earth block masonry to existing European masonry standard EN 1996[4] is therefore logical and recommendable. The main purpose of the present study was a first calibration of safety elements on the resistance side assisted by testing.
2. EXPERIMENTAL PROGRAM

2.1 Materials

Earthen materials were sourced from local manufacturers of prefabricated earthen building products. Two types of earth block (3DF and NF, Fig. 1 a-b) and two types of earth mortar (M2 and M3) combined to four types of earth block masonry were tested under uniaxial compression. Earth block and mortar samples were prepared according to DIN 18945 [2] and DIN 18946 [3]. Earth block masonry wallets were produced by laying six earthen block courses in accordance with EN 1052-1 [5]. Samples were built with pre-wetting of joint contact surfaces by submerging the blocks into water of 10 mm height for approx. 10 seconds. After production, all samples were stored in a climate room at 23°C and 50% relative humidity (RH) for drying. Samples were removed from the climate room shortly before compression tests.

2.2 Uniaxial compression tests

Compressive strength and Young’s modulus of the earth blocks was determined on a 1 MN universal testing machine. For the measurement of displacement, linear variable differential transformers (LVDTs) were used. The compressive strength tests were carried out according to DIN 18945 [2]. Tests of mortar samples were performed on a 10 kN servo mechanical testing machine. Tests of masonry wallets were performed using a 1 MN universal testing machine. Samples were tested under displacement control according to EN 1052-1[5]. The loading speed was adjusted in a way that the failure point was reached within 15–30 minutes. Deformations were monitored by LVDTs parallel and perpendicular to the loading direction on both sides of the wallets (Fig. 1c-d).

![Fig. 1. Extruded hollow block 3DF (a) and solid block NF produced by a mechanised hand moulding procedure (b). Uniaxial compression tests: test setup for NF earth block masonry (c) and 3DF earth block masonry (d).](image)

2.3 Test results

The deformation of the earth block samples was fairly high, which resulted in a relatively low Young’s modulus of approx. 1000–1200 N/mm². However, the compressive strength of the earth blocks (3.6–5.6 N/mm²) was fairly high and showed a limited scatter in results. Mortar samples yielded a compressive strength of 3.3–3.8 N/mm². The mean and characteristic values of compressive strength and Young’s modulus for earth block and earth mortar samples are listed in Table 1. For earth block masonry wallets, strength
values are in the range of 2.0–3.7 N/mm². Ultimate vertical strain varied in the range of 0.4–0.6 %. On the longitudinal side of the samples, failure was visible by vertical cracks above and beneath the butt joints, and mortar spallings in the bed joints. The front side showed a cone-shaped failure pattern. Both are typical failure modes of masonry due to exceedance of the blocks tensile strength (Fig. 2). The stress-strain curves shown in Fig. 3, exhibit a linear development until approximately one third of the maximum compressive strength. Subsequently the curves indicate a slightly non-linear behaviour until the maximum strength and finally show a phase of post-peak strain softening. The failure mode under compression loading is rather brittle and the stress-strain behaviour is similar to conventional masonry. Table 2 lists the mean and characteristic values of compressive strength and Young’s modulus for masonry wallets. A more detailed description of the test methods, results and conclusions can be found here [6].

Table 1. Results of uniaxial compression tests of earth block and earth mortar samples (κ = smallest singular value; SD = standard deviation; COV = coefficient of variation in %).

<table>
<thead>
<tr>
<th>Sample</th>
<th>width × height × thickness (mm)</th>
<th>Compressive strength (N/mm²)</th>
<th>Compressive strength normalised (N/mm²)</th>
<th>Young’s modulus (N/mm²)</th>
<th>n° of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean κ</td>
<td>SD</td>
<td>COV</td>
<td>Mean κ</td>
<td>SD</td>
</tr>
<tr>
<td>Earth block</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NF</td>
<td>240 × 115 × 71</td>
<td>5.65</td>
<td>5.29 0.16 2.8</td>
<td>4.68 4.36 0.13 2.8</td>
<td>1051</td>
</tr>
<tr>
<td>NF</td>
<td>120 × 115 × 142</td>
<td>4.47</td>
<td>4.28 0.11 2.5</td>
<td>- - -</td>
<td>1199</td>
</tr>
<tr>
<td>3DF</td>
<td>240 × 175 × 115</td>
<td>3.58</td>
<td>3.40 0.10 2.8</td>
<td>- - -</td>
<td>998</td>
</tr>
<tr>
<td>Mortar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>160 × 40 × 40</td>
<td>3.34</td>
<td>- 0.23 6.8</td>
<td>- - -</td>
<td>- - -</td>
</tr>
<tr>
<td>M3</td>
<td>160 × 40 × 40</td>
<td>3.78</td>
<td>- 0.16 4.3</td>
<td>- - -</td>
<td>- - -</td>
</tr>
</tbody>
</table>

a entire block, b half block.

Table 2. Results of the uniaxial compression tests of earth block masonry samples (SD = standard deviation; COV = coefficient of variation in %).

<table>
<thead>
<tr>
<th>Masonry sample</th>
<th>width × height × thickness (mm)</th>
<th>Compressive strength (N/mm²)</th>
<th>Young’s modulus (N/mm²)</th>
<th>n° of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean κ</td>
<td>SD</td>
<td>COV</td>
<td>5%-q</td>
</tr>
<tr>
<td>MW_NF_M3</td>
<td>500 × 500 × 115</td>
<td>3.74</td>
<td>0.14</td>
<td>3.8</td>
</tr>
<tr>
<td>MW_NF_M2</td>
<td>500 × 500 × 115</td>
<td>3.46</td>
<td>0.07</td>
<td>1.9</td>
</tr>
<tr>
<td>MW_3DF_M3</td>
<td>500 × 620 × 175</td>
<td>1.99</td>
<td>0.09</td>
<td>4.5</td>
</tr>
<tr>
<td>MW_3DF_M2</td>
<td>500 × 620 × 175</td>
<td>2.02</td>
<td>0.15</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Fig. 2. NF earth block masonry (a-b) and 3DF earth block masonry (c-d) under uniaxial compression. Cracks are marked in yellow lines, spallings in red circles.
2.4 Evaluation and comparison of results

The test results of the earth blocks and mortars show fairly low variations of the compressive strength. On the one hand this is based on the fact that only one charge of one manufacturer of blocks respectively mortar was tested but on the other hand this indicates high quality of industrial production. The development of product standards such as DIN 18945 [2] and DIN 18946 [3] can be considered as a main reason for this. The variation of the compressive strength of the wallettes is fairly low as well. As expected, the compressive strength of the solid block masonry is notably higher than the one of the hollow block masonry (Table 2). The compressive strength variation between the wallettes with different types of mortar is fairly slight. In general the experiments showed that the load-bearing behaviour and failure mechanisms of earth block masonry are similar to conventional masonry. Hence, mechanical models and design rules can be transferred.

3. PARTIAL SAFETY FACTOR

3.1 Calibration

The partial safety factor for earth block masonry under compression loading, based on the results obtained in this study and using the method of calibration, given in EN 1990 [7] is determined by the equation 1:
\[
\gamma_R = \frac{R_k}{R_d} = \frac{m_R - k \cdot \sigma_R}{m_R - \alpha_R \cdot \beta \cdot \sigma_R} = \frac{1 - k \cdot COV_R}{1 - \alpha_R \cdot \beta \cdot COV_R}
\]

(1)

Where the fractile-factor \( k \), the sensitivity factor on the resistance side \( \alpha_R \) and the index of reliability \( \beta \) are given in EN 1990 [7]. Using a COV of 4.4% (mean value of the COV of the 4 testing series) the safety factor given is 1.1. This does certainly not reflect the realistic variability of earth block masonry made with blocks belonging to one compressive strength class. The COV will be higher when sample blocks are sourced from different batches and different manufacturers. Considering a realistic scatter of the bearing capacity the COV needs to be estimated. For masonry under centric uniaxial compression loading, the COV of the bearing capacity is estimated in the range of 20–25% [8]. The partial safety factor for a COV of 20% increases then to 1.6. The wide range of these values shows the sensitivity of the partial safety factor to the statistical characteristics, especially the stochastic variation of compressive strength. In the following paragraph the results will be discussed and a recommendation referring the partial safety factor will be given.

3.2 Discussion of the results

The applied method for the calibration of a partial safety factor in accordance with EN 1990 [7] represents a simple manner to determine safety elements in the field of construction. The partial safety factor on the resistance side thereby can be specified regardless of the design situation and the stochasticity within the action effects. Nowadays, most of the safety factors on the resistance side in the European standards are evaluated this way. A solid database providing bearing capacity and statistical characteristics is needed for an exact determination of safety elements. With regard to conventional masonry more than 2000 compressive strength tests were carried out to elaborate the allowable stresses and the safety elements [9]. No such database is existing for earth block masonry. On the basis of the presented test results and taking into account a realistic estimation of the COV of the bearing capacity of earth block masonry, a partial safety factor on resistance side under compression loading of 1.75 is recommended. This recommended value should not be regarded as an absolute value but as an approximation of its range. The application of more exact methods, like iterative optimisation methods for a precise determination of the failure reliability, does not seem to be appropriate at the moment. More detailed data about the statistical characteristics of earth block masonry related to the earth blocks compressive strength classes is needed.

4. CONCLUSIONS AND OUTLOOK

This paper presents an analysis of the load-bearing behaviour and the statistical characteristics of earth block masonry under compression loading. A partial safety factor for the structural design of earth block masonry according to the masonry code EN 1996 [4] is recommended. The results provided reliable statistical characteristics referring the compressive strength of earth blocks, earth mortar and earth block masonry. The partial safety factor on the resistance side was determined based on these results and the reliability method. The variability of the single components was fairly low, indicating high quality standards with regard to industrial production. With the masonry wallets the post-peak strain
performance was determined, showing again fairly low variation of the bearing capacity, which was also due to the fact that only two types of earth block and two types of earth blocks were used.

The presented experiments provide a first valid database regarding the statistical characteristics of earth block masonry under compression loading. The load-bearing behaviour and the failure mechanisms are similar to conventional masonry. A realistic estimation of the COV leads to a partial safety factor in the range of the safety factors for conventional masonry. Future research will mainly focus on the development of a comprehensive database for earth block masonry. In this process different load conditions, like shear stress in and perpendicular to the panel plane and combined bending and compression load, need to be investigated. Furthermore, the influence of RH on the load-bearing behaviour of earth block masonry needs to be accurately assessed.

References


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Philipp Müller is a Research Associate at the Singapore Centre of Eidgenössische Technische Hochschule Zürich. He obtained his Master of Science in Civil Engineering with distinction from Technische Universität Berlin in 2014. Employee at Bundesanstalt für Materialforschung und -prüfung BAM and Ziegert | Seiler Ingenieure 2013 – 2015. His main research focuses on structural reliability of alternative construction materials.
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