1. ABSTRACT

The paper presents the results of investigations on the suitability of highly perforated clay-brick units (35% up to 50% by volume of formed vertical holes) and lightweight mortar for reinforced masonry. These materials are not standardized in the current German code DIN 1053 part 3 "Reinforced Masonry" /1/ due to lack of test results concerning the compressive strength parallel to the bed-joints, the out-of-plane shear-strength and the bond strength between reinforcement and lightweight mortar in bed-joints. Proposals for design values for reinforced clay-brick masonry are given on the basis of the investigations.

2. INTRODUCTION

The use of bed-joint reinforcement in traditional vertically-perforated clay-brick masonry is an interesting alternative to reinforced concrete structures. Examples for these structures are ring anchors and ring beams, see Fig. 1, as well as reinforced cellar walls exposed to lateral soil pressure. The application of reinforced vertically-perforated clay-brick masonry requires a number of design values, e.g. for the compressive strength parallel to the bed-joints, the out-of-plane shear-strength and the bond strength between reinforcement and lightweight mortar in bed-joints. These design values have to be derived from test results if regulations in current standards are not available.

Keywords: Reinforced Masonry, Bed-Joint Reinforcement, Vertically-Perforated Clay-Bricks, Lightweight Mortar, Characteristic Anchorage Bond Strength

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3. REGULATIONS IN CURRENT MASONRY CODES

The current German code DIN 1053 part 3, edition 02.90, contains some restrictions concerning the materials approved for reinforced masonry construction. Units with more than 35% of formed vertical holes are not allowed with respect to the unknown load-bearing capacity of these units in out-of-plane bending at that time. The design values for the compressive strength of masonry parallel to the bed-joints for units with less than 35% of formed vertical holes are reduced to 50% of the values for loading normal to the bed-joints. Mortars are restricted to M10 or greater with respect to the then uncertain anchorage bond properties between reinforcement and other mortars. Reinforcement has to consist of corrosion-protected ribbed rebars. The maximum bar diameter is given for certain conditions of application (bed-joints, recesses) in order to obtain a proper embedment of the reinforcement. The use of prefabricated bed-joint reinforcement has to be regulated by national technical approvals. The main reason for these restrictions was the lack of test results for other types of materials.

The current draft of Eurocode 6/2/ contains no specified requirements concerning units approved for reinforced masonry. As there are no values for anchorage bond for mortars M4 or lower as well as for lightweight and thin layer mortar, these mortars are not allowed. Reinforcement, plain or ribbed with equivalent corrosion protection, should be in accordance with EN 10080 or EN 10088 respectively.

4. NECESSARY RESEARCH ACTIVITIES

The large majority of the vertically-perforated clay-bricks in Germany which were especially developed to meet the high requirements concerning thermal insulation do not meet the requirements concerning the maximum percentage of formed vertical holes in the German Code on Reinforced Masonry. The application of these units in bed-joint reinforced masonry is nevertheless desirable. The aim of an extensive test programme, sponsored by the German Clay Brick Industry /3/ was the derivation of design methods for vertically-perforated clay-bricks in reinforced masonry based on test results. These results were the base for the draft of a national technical approval /4/. An additional test programme /5/ had the aim to determine suitable values of bond stresses for
reinforcement in very frequently used lightweight mortars LM 700, LM 1000 and general purpose mortar M5.

5. TEST PROGRAMME

5.1 Load-bearing Capacity of Bed-joint Reinforced Clay-brick Masonry Subjected to Out-of-plane Shear and Bending

The load-bearing capacity of bed-joint reinforced clay-brick masonry was checked in full-scale flexural tests on reinforced walls. The tests were carried out with 3 types of units (44 to 48 % of formed vertical holes), general purpose mortar M 10 and lightweight mortar LM 1000. The walls, height $h = 1.00$ m, were designed for a combined shear/bending (compression zone) failure, see fig. 2 and were reinforced with 1 epoxy-coated rebar $d_s = 8$ mm in every bed-joint (vertical bar spacing 250 mm). The compressive strength of the units normal and parallel to the bed-joints was determined in addition. All types of units used had straight shells parallel to the compressive force in out-of-plane bending.

![Fig. 2: Specimen for out-of-plane-bending tests on reinforced clay-brick masonry](image)

5.2 Bond between Mortar and Bed-joint Reinforcement

The bond between mortar and bed-joint reinforcement is strongly influenced by the mortar properties in the joint. The influences of units and mortar on these properties were checked in an additional test programme reported elsewhere in these proceedings /6/. Using the most unfavourable unit-mortar reinforcement combinations, a series of pull-out tests was carried out with 3 different types of units, lightweight mortars LM 700, LM 1000, general purpose mortar M 5 and different diameters of epoxy-coated reinforcement. The test set-up for the pull-out tests is shown in Fig. 3.
6. SELECTED TEST RESULTS

6.1 Load-bearing Capacity of Bed-joint Reinforced Clay-brick Masonry Subjected to Out-of-plane Shear and Bending

Table 1 shows some selected test results. The compressive strength of the units parallel to the bed-joints was in a range of 28 to 37% of the compressive strength normal to the bed-joints. All walls failed in out-of-plane shear due to unit failure. This proves that the design values used for shear were more appropriate than the values for the compressive strength parallel to the bed-joints. The out-of-plane shear strength of the walls was in the range of 0.13 to 0.15 N/mm². An influence of the type of mortar (M10 or LM1000) on the shear strength was not observed. These values, reduced with a partial safety factor γ = 2.1 are well above the design values given in the German code as

\[ \tau_{0,1} = 0.015 \cdot \beta_R = 0.056 \text{ N} / \text{mm}^2. \]  

<table>
<thead>
<tr>
<th>unit</th>
<th>mortar</th>
<th>( f_{c,u} )</th>
<th>( f_{c,u} / f_{c,u} )</th>
<th>( f_{v} )</th>
<th>( f_{c,ma} )</th>
<th>( f_{c,ma} / \beta_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLz 8-10DF</td>
<td>M 10</td>
<td>13,1</td>
<td>-</td>
<td>0.15</td>
<td>2.4</td>
<td>0.64</td>
</tr>
<tr>
<td>HLz 8-10DF</td>
<td>LM 1000</td>
<td>12,2</td>
<td>0.28</td>
<td>0.15</td>
<td>2.4</td>
<td>0.90</td>
</tr>
<tr>
<td>HLz 8-15DF</td>
<td>M 10</td>
<td>10,9</td>
<td>0.32</td>
<td>0.13</td>
<td>2.1</td>
<td>0.56</td>
</tr>
</tbody>
</table>

The compressive stress in the pressure zone of the walls at shear failure was calculated from the equilibrium of the internal forces as 56 to 64% of the design compressive
strength $\beta_R$ normal to the bed-joints for the walls with general purpose mortar M 10 and 90% of the design compressive strength $\beta_R$ normal to the bed-joints for the wall with lightweight mortar LM 1000. These values are in the range of the values determined in pure compression on two-unit prisms, where values between 54 and 73% were determined. The real compressive strength in out-of-plane bending must be even higher. These results are not surprising, because the external shell of the units which determines the strength of the bending pressure zone is normally thicker and therefore stronger than the inner shells which are determining the ultimate load in pure compression.

6.2 Bond between Mortar and Bed-joint Reinforcement

The compressive strength of the general purpose mortar M 5 in the joint is significantly influenced by the state of humidity of the units. Table 2 shows some selected test results. The compressive strength in combination with dry units $f_{c,j} = 12.2 \text{ N/mm}^2$ was almost 250% higher than in wet units, $f_{c,j} = 4.9 \text{ N/mm}^2$. This had a significant influence on the bond properties. The combination of wet clay-brick units and M 5 turned out to be the worst case for bond failure too.

**Table 2. Bond between mortar and bed-joint reinforcement (Different vertically perforated clay-bricks); state of humidity of the units (d=dry, w=wet), type of mortar, diameter $d_s$ of steel, compressive strength $f_{c,j}$ of mortar in the joint, mean bond stress $f_{bu}$ in the ultimate limit state, mean anchorage length $l_{bu}$ in the ultimate limit state**

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Mortar</th>
<th>$d_s$ mm</th>
<th>$f_{c,j}$</th>
<th>$f_{bu}$</th>
<th>$l_{bu}$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>LM 1000</td>
<td>5</td>
<td>12.6</td>
<td>2.84</td>
<td>220</td>
</tr>
<tr>
<td>w</td>
<td>LM 1000</td>
<td>5</td>
<td>16.0</td>
<td>4.01</td>
<td>156</td>
</tr>
<tr>
<td>d</td>
<td>LM 1000</td>
<td>8</td>
<td>11.4</td>
<td>1.74</td>
<td>611</td>
</tr>
<tr>
<td>d</td>
<td>LM 1000</td>
<td>8</td>
<td>11.8</td>
<td>2.15</td>
<td>482</td>
</tr>
<tr>
<td>d</td>
<td>LM 1000</td>
<td>8</td>
<td>16.4</td>
<td>2.42</td>
<td>413</td>
</tr>
<tr>
<td>d</td>
<td>LM 1000</td>
<td>8</td>
<td>10.5</td>
<td>1.65</td>
<td>606</td>
</tr>
<tr>
<td>d</td>
<td>LM 700</td>
<td>5</td>
<td>4.7</td>
<td>0.94</td>
<td>668</td>
</tr>
<tr>
<td>w</td>
<td>LM 700</td>
<td>5</td>
<td>5.7</td>
<td>1.32</td>
<td>494</td>
</tr>
<tr>
<td>d</td>
<td>M 5</td>
<td>5</td>
<td>12.2</td>
<td>3.80</td>
<td>165</td>
</tr>
<tr>
<td>w</td>
<td>M 5</td>
<td>5</td>
<td>4.9</td>
<td>1.74</td>
<td>362</td>
</tr>
</tbody>
</table>

Figure 4 shows the mean bond-slip relationships of rebars $d_s = 5 \text{ mm}$ with selected lightweight and general purpose mortars. The transmissible bond forces between reinforcement and mortar LM 1000 (aggregate: expanded clay) were, regardless of the state of humidity of the units, significantly higher than those of general purpose mortar M 5 used with wet units.

The compressive strength in the joint $f_{c,j}$ of the lightweight mortars used in the tests was only slightly influenced by unit properties. For the small diameters $d_s = 5 \text{ mm}$ a close correlation between the mean bond stresses $f_{bu}$ in the ultimate limit state, derived with the bond theory by Rehm /7/, and the compressive strength of mortar in the joint was observed. The bond properties for diameters $d_s = 8 \text{ mm}$, the greatest diameter allowed in bed-joints according to DIN 1053 part 3 were significantly poorer than for $d_s = 5 \text{ mm}$. 

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Figure 4: Bond($\tau_v$)-slip($\Delta$) relationship for different mortars and reinforcing steel $d_s = 5$ mm

Figure 5 shows the relationship between the bond stresses $f_{bu}$ in the ultimate limit state and the compressive strength of mortar in the joint for different diameters and different lightweight aggregates. The relationship

$$f_{bu} = 0.17 \cdot f_{CJ}^{1.14}$$  \hspace{1cm} (2)

could be established for lightweight mortar and diameter $d_s = 5$ mm. For diameters $d_s = 8$ mm, the relationship

$$f_{bu} = 0.28 \cdot f_{CJ}^{0.78}$$  \hspace{1cm} (3)

was established. The ruling parameter for the bond between lightweight mortar and reinforcement is the shear strength between mortar and unit. The shear strength in specimens built of dry clay-brick units is significantly lower compared with specimens with wet units. This causes a different type of bond failure mechanism. This mechanism, the splitting failure, is characterized by longitudinal cracks along the rebar, caused by the inferior bond between unit and mortar. The problem of splitting failure has been investigated for rebars in concrete with small concrete cover /8/. In case of splitting failure, the reduction of transmissible bond stresses compared to the case of pull-out failure was determined as 25 to 40 %, depending on the thickness of the concrete cover. This explains the even poorer bond properties of diameters $d_s = 8$ mm compared with diameters $d_s = 5$ mm, see fig. 6.
Fig. 5: Bond strength $f_{bu}$ and compressive strength $f_{c,j}$ of mortar in the joint

Fig. 6: Bond($\tau_v$)-slip($\Delta$) relationship
Mortar LM 1000, aggregate: expanded clay
Different states of humidity, different diameters $d_s$
7. DERIVATION OF DESIGN VALUES FOR REINFORCED VERTICALLY-PERFORATED CLAY-BRICK MASONRY

The now available test data can be used for the derivation of design values for vertically-perforated clay-bricks in bed-joint-reinforced masonry. A complex design method suitable for all types of unit-mortar combinations was not the aim of the investigations, so that some important material properties have to be defined as boundary conditions for the application of the proposed design values.

The mean compressive strength of the units in longitudinal direction has to be restricted to

\[ f_{\text{cl,m}} \geq 3,50 \text{N/mm}^2 \]  

(4)

as the minimum mean compressive strength of the units used in the tests. These units must have straight shells in direction of the compressive stress due to out-of-plane bending and have to be used in combination with general purpose mortars M 10 or stronger.

Taking these restrictions into account, the design of reinforced clay-bricks masonry with units having an area of formed vertical holes of 35 up to 50 % can be carried out according to DIN 1053 part 3. This means especially, that the compressive strength in the external fibre of the pressure zone in bending can be taken as

\[ f_{\text{cl,ma}} = 0,50 \cdot \beta_R. \]  

(5)

The design values (basic values) for out-of-plane shear given in DIN 1053 part 3:

\[ \tau_{011} = 0,015 \cdot \beta_R \]  

(6)

as a function of the design value \( \beta_R \) for the compressive strength of masonry can also be applied to reinforced vertically-perforated clay-brick masonry, if the maximum design value is restricted to

\[ \beta_R \leq 3,75 \text{N/mm}^2. \]  

(7)

These regulations are part of the draft of a technical approval /4/ for vertically-perforated clay bricks in bed-joint-reinforced masonry.

Design values for the anchorage bond strength can be derived from the test results in /5/. The German concept for the determination of basic values of bond stresses between mortar and bed-joint reinforcement foresees a reduction of the mean stresses in the ultimate limit state by a safety factor of \( \gamma = 3,0 \) to characteristic values \( f_{\text{bok}} \). This factor \( \gamma \) includes influences from the scatter of test results, permanent loads and poor embedment. The characteristic values \( f_{\text{bd}} \) have to be reduced by a safety factor of \( \gamma = 2,1 \) (against the ultimate limit state) to design values \( f_{\text{bd}} \).

Applying this method and taking eq. (3) as the worst case for bed-joint reinforced clay-brick masonry into account, the values given in Table 3 are obtained.
A comparison between the characteristic bond strength proposed as result of the investigations in /5/ and the empiric calculation method proposed in /9/ has been made for general purpose mortar M 5. The design bond strength $f_{bd}$ for ribbed bars in /9/ is a function of the tensile strength of concrete

$$f_{bd} = \frac{2,25 \cdot f_{ctk,0.05}}{\gamma_c}$$

with $f_{bd}$: design bond strength
$f_{ctk,0.05}$: 5%-quantile of the tensile strength of concrete ~ 0,70 $f_{ctk}$
$\gamma_c$: safety factor, $\gamma_c = 1,5$

With the relation between compressive and tensile strength of mortar in the joint determined in /10/

$$f_{t,j} = 0,15 \cdot f_{c,j}^{0.66}$$

with: $f_{t,j}$ tensile strength of mortar in the joint
$f_{c,j}$ compressive strength of mortar in the joint

the design bond strength $f_{bd}$ for ribbed bars in mortar M 5 can be approximately determined as

$$f_{bd} = 1,5 \cdot 0,7 \cdot 0,15 \cdot 5^{0.66} = 0,46 \text{ N/mm}^2.$$ (10)

This value is valid for a good bond quality. For other conditions (bed-joint reinforcement, reduction of the rib-heights by the epoxy-coating), an additional reduction factor of 0,7 should be introduced according to /9/. With this reduction, the design bond strength $f_{bd}$ can be determined as

$$f_{bd} = 0,7 \cdot 0,46 = 0,32 \text{ N/mm}^2 \approx 0,30 \text{ N/mm}^2$$ (11)

This corresponds very well with the proposed value derived from the test results. The value for the characteristic bond strength $f_{bok} = 1,0 \text{ N/mm}^2$ given in Eurocode 6 is significantly higher. Further discussion on these values seems indispensable.
8. CONCLUSIONS

The design of load-bearing reinforced masonry with vertically-perforated clay-bricks is possible applying the drafted national technical approval /4/ and the suggested amendment concerning the use of lightweight mortar LM 1000 in reinforced clay-brick masonry.

A discussion of the values for the anchorage bond strength indicated in Eurocode 6 is indispensable. As a result of this discussion, appropriate values for anchorage bond should be defined for different boundary conditions (bed-joints, chases, cavities). Values for the anchorage bond strength between lightweight mortar LM 1000 and reinforcement should be included in Eurocode 6.

9. REFERENCES

/1/ DIN 1053 Teil 3 02.90. Mauerwerk; Bewehrtes Mauerwerk; Berechnung und Ausführung