Effects of Technology of Placing Different Types of Reinforcement in Bed Joints on Compressive and Shear Strength of AAC Masonry Walls

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Abstract. Reinforcement for bed joints in masonry structures is commonly applied to prevent crack propagation and to increase values of cracking stress, and compressive or shear strength. Recommendations on construction only suggest that a cladding layer of mortar should be uniformly applied to top and bottom parts of the reinforcement. This paper presents results from testing reinforced and unreinforced masonry walls made of AAC (Autoclaved Aerated Concrete). Main tests were performed on 12 wall elements with the length \( l = 1180 \) m, height \( h = 1208-1212 \) mm, and thickness \( t = 180 \) mm. All the walls were reinforced with steel truss structures or fiberglass meshes. We used single mortar laying in all six models, where the reinforcement was embedded into mortar. The double mortar laying was applied in other six models. The models were subjected to compression in accordance with European code PN-EN 1052-1:2000 and diagonal tension in accordance with American code ASTM E519-81. We compared the obtained results of cracking force and stress with the tests (Jasiński, Drobiec 2016) on walls with and without steel truss. The technology of placing reinforcement was similar. We demonstrated that single mortar laying led to noticeably lower values of cracking and failure stresses in comparison to the unreinforced walls. A favourable increase in compressive and shear strength was observed for the technology of double mortar laying.

1. Introduction

Low compressive and tensile strength of autoclaved aerated concrete often requires reinforcement to limit the development of cracks, and thus to increase its compressive and tensile strength. Building reinforcement into bed joints of the wall is the simplest method. The standard PN-EN 1996-1-1:2010 [1] specifies how to build reinforcement into bed joints, and particularly defines conditions for joints of standard thickness \((t_m > 8 – 15 \) mm). There are no recommendations for bedding reinforcement on walls with thin joints \((t_m > 0,5 – 3 \) mm), but in such cases guidelines of manufacturers are followed. Unfortunately, they do not define how to ensure the proper cover of reinforcement in the bed joint. Properties of the wall with reinforcement built with different technologies require various covers [2, 3]. The authors conducted tests on more than ten walls with reinforcement covered with mortar using different technologies. It was done intentionally to choose the most optimal method and eliminate the least advantageous one. For the tests, we used wall units made of AAC (Autoclaved Aerated Concrete)
with density of 600 kg/m³, with thin joints made of M5 class mortar. Reinforcement was composed of steel truss and fibreglass meshes.

2. Test models, technology of preparing test elements and the scenario of tests
Test models were prepared from AAC blocks \( f_b = 4.0 \, \text{N/mm}^2 \) with dimensions of 600×240×180 mm. They were produced by a Polish manufacturer, and bedded in masonry mortar of M5 type \( f_m = 6.1 \, \text{N/mm}^2 \). Steel truss structures of EFZ 140/Z 140 type (design strength of strip steel \( f_y = 685 \, \text{N/mm}^2 \) and TBM Reinforcement Fiberglass Geogrid (maximum strength of 1m of mesh determined acc. to ASTM D 6637 [4], method A - testing a weft - 38.7 kN/m, testing a warp – 22.7 kN/m). Amount of reinforcement corresponded to the minimum value recommended by PN-EN 1996-1-1:2010 [1]. Compressive strength of masonry (PN-EN 1052-1:2000 [5]) was \( f_{c,m,v} = 2.97 \, \text{N/mm}^2 \) \( (f_k = 2.48 \, \text{N/mm}^2) \), and modulus of elasticity was \( E_{cm} = 2040 \, \text{N/mm}^2 \). The test models with the same arrangement of masonry units were prepared for compressive and shear tests. The models were composed of 5 layers of blocks. In each layer, there were two AAC blocks and the applied bonding units had a length of \( u = 300 \, \text{mm} \). In the models with a one-side mortar, the joint thickness was 2 mm (Figure 1a), and in the models with a two-side mortar, the joint thickness was 3 mm (Figure 1b).

![Figure 1. Arrangement of masonry units in test models: a) series with mortar applied on one side, b) series with mortar applied on both sides](image)

The technology of applying mortar on one side of the reinforcement consisted in preparing the surface, applying the mortar with a special feeder and building reinforcement (steps 1, 2 and 3), and then applying a top layer of blocks (step 4) – Table 1. In the technology of applying mortar on both sides of the reinforcement, the first three steps were the same, but in step 4 mortar was applied on the support area of the top layer of blocks. In step 5, the top block with a mortar layer was placed on the bed joint with bedded reinforcement – Table 1. In both methods, step 6 consisted in adjusting blocks with a rubber hammer. The elements were reinforced with steel truss, EFZ 140/Z 140 type. Its strips were made of flat bars with rectangular cross-section equal to 8x1.5 mm, and struts made of wire with a diameter of 1.5 mm – Figure 2a. We also applied the structural reinforcement for bed joints – TBM Reinforcement Fiberglass Geogrid with aperture size 10×10 mm – Figure 2b. The geogrid was composed of a woven weft with double weaving and a diameter of 0.5 mm, and a flat warp woven with a rectangular cross section of 0.25×1.5 mm. The scenario of tests on compression and diagonal compression is shown in Table 2.
Figure 2. Structural reinforcement used in tests: a) steel truss of EFZ 140/Z 140 type, b) TBM
Reinforcement Fiberglass Geogrid: 1 – truss strips, 2 – truss struts, 3 – fibres of mesh weft, 4 – fibres
of mesh warp

Table 1. Technology of preparing models

| Step | Applying mortar on one side | Applying mortar on both sides | Description of actions |
|------|----------------------------|-----------------------------|------------------------|
|      | Applying mortar on one side | Applying mortar on both sides | Applying mortar on one side | Applying mortar on both sides |
| 1    |                            |                            | Placing single elements and compensating support areas. |
| 2    |                            |                            | Applying the mortar layer with a thickness of 3 mm. |
| 3    |                            |                            | Bedding reinforcement in the mortar layer. |
| 4    |                            |                            | Placing the top layer of masonry units. Applying the mortar layer with a thickness of 3 mm on the top block. |
| 5    |                            |                            | Placing the top layer of masonry units. |
| 6    |                            |                            | Adjusting masonry units with a rubber hammer. |
### Table 2. Scenario of tests

| Name of series | Test | Technology of reinforcement | Type of reinforcement | Reinforcement % | Number of test elements |
|----------------|------|-----------------------------|-----------------------|----------------|------------------------|
| S2StM-I        |      | One-side application of mortar | TBM reinforcement      | 0.1            | 3                      |
| S2StM-II       |      | Two-side application of mortar | TBM reinforcement      |                | 3                      |
| S1Zk           |      | One-side application of mortar | EFZ 140/Z 140 reinforcement | 0.07          | 3                      |
| RL-S-Z3-1-3    |      | One-side application of mortar | TBM reinforcement      |                | 3                      |
| RL-S-Z3-4-6    |      | Two-side application of mortar | TBM reinforcement      | 0.1            | 3                      |
| RL-S-Z1-1-3    |      | One-side application of mortar | TBM reinforcement      |                | 3                      |
| RL-S-Z1-4-6    |      | Two-side application of mortar | TBM reinforcement      | 0.07           | 3                      |

### 3. Testing technique

#### 3.1. Compression tests on walls

Tests were performed on masonry elements at least 28 days from finishing works. The test was conducted in a hydraulic press with a capacity of 2000 kN. The test elements were placed between platens of the hydraulic press, in the central position, without eccentricity of loading. There was a full contact between the top and bottom surface of the elements and platens of the strength testing machine. During the tests, a dynamometer measured compressive force with the accuracy of 0.001 kN, and inductive sensors measured horizontal and vertical displacements with the accuracy of 0.002 mm. Dimensions of a base for measuring wall displacement were determined in accordance with PN-EN 1052-1:2000. The length of vertical and horizontal sides of the measuring bases were the same, equal
to 620 mm. The detailed procedure and test results are described in [6, 7]. The measurement of vertical strains was used to determine the vertical stress $\sigma_y$ – vertical strain $\varepsilon_y$ relationships. And the measured horizontal strains were used to determine Poisson's ratio $\nu$ of masonry unit. The tests were conducted with an automated measuring stand. Displacements and compressive force were measured every 0.5 s. The loading rate was applied in accordance with PN-EN 1052-1:2000 to reach the maximum force after 15-30 minutes from the commencement of loading. We also recorded the force, at which the first visible crack occurred in the test element. To determine values of cracking and failure stress, a force was divided by the measured cross-section area of the test element according to the following relationships:

- cracking stress

$$\sigma_{cr} = \frac{F_{cr}}{A_h}$$

$\sigma_{cr}$ – normal compressive stress, at which first visible cracks with the width of 0.1-0.3 mm occurred,
$F_{cr}$ – compressive force read at the moment of formation of first visible cracks with the width of 0.1-0.3 mm,
$A_h$ – cross-section area of masonry ($0.18 \times 1.18 \, \text{m} = 0.212 \, \text{m}^2$),

- failure stress

$$\sigma_u = \frac{F_u}{A_h}$$

$\sigma_u$ – normal compressive stress observed at the highest applied force,
$F_u$ – the highest recorded compressive force,
$A_h$ – cross-section area of masonry.

3.2. Diagonal compression tests on walls

The test elements $l$ were bedded in special steel slots, where one diagonal was set vertically and arms of the steel slot covered ca. 1/10 of length (height) of the test element (ASTM E519-81 [8]). The detailed procedure and the description of the test stand are discussed in [3]. For each recorded force $F_i$ (at $i$-th level of loading), we calculated the average of tangential stress $\tau_{i,t}$ as a ratio of the load $F_i$ to the vertical section area of masonry (along the diagonal) $A_h$ from the following relationship: A frame structure (with the base of 932 mm) was used to measure shear angle of the masonry. The structure was fixed at both sides of the test model. Shear angle $\Theta$ separated from the deformed measuring system was calculated from trigonometric relationships on the basis of changes in the length of sides and diagonals.

Values of cracking stress $\tau_{cr}$ were determined from cracking forces $F_{cr}$, at which new cracks with the width of 0.1 – 0.3 mm were observed. Failure stress $\tau_{w}$ was determined at forces causing destruction of the model (further increase in loading at increasing shear strain values of the masonry).

To determine values of cracking and failure stress, a force was divided by the measured cross-section area of the test element according to the following relationships:

- cracking stress

$$\tau_{cr} = \frac{F_{cr}}{A_h} = \frac{F_{cr}}{\sqrt{t^2 + t^2}}$$

$\sigma_{cr}$ – shearing stress, at which first visible cracks with the width of 0.1-0.3 mm occurred,
$F_{cr}$ – compressive force read at the moment of formation of first visible cracks with the width of 0.1 – 0.3 mm,
$t = 180 \, \text{mm}$ – thickness of masonry,
$l = 1180 \, \text{mm}$ – length of masonry,
$h = 1208 \, \text{mm}$ or $1212 \, \text{mm}$ – height of masonry.
$A_h$ – vertical section area of masonry.

- failure stress:
\[ \tau_u = \frac{F_u}{A_h} = \frac{F_u}{t^2 \sqrt{l^2 + h^2}} \] 

where:
- \( \tau_u \) – shearing stress at the highest observed force,
- \( F_u \) – the highest recorded compressive force,
- \( A_h \) – vertical section area of masonry.

To evaluate the effect of technology of placing the reinforcement on compression and shearing, we introduced the parameter \( \chi \). It was a ratio of maximum values of normal or diagonal stress for models with and without reinforcement, expressed with the following relationships:

- **axial loading:**
  \[ \chi_c = \frac{\sigma_{u,cR}}{\sigma_{u,cN}} \] 
  \( \chi_c \) – a parameter taking into account the technology of masonry building under compression,
  - \( \sigma_{u,cR} \) – compressive stress, at which the reinforced masonry is destroyed,
  - \( \sigma_{u,cN} \) – compressive stress, at which the unreinforced masonry is destroyed,

- **diagonal compression:**
  \[ \chi_{dc} = \frac{\tau_{u,cR}}{\tau_{u,cN}} \] 
  \( \chi_{dc} \) – a parameter taking into account the technology of masonry building under compression,
  - \( \tau_{u,cR} \) – failure stress for the reinforced masonry under diagonal compression,
  - \( \tau_{u,cN} \) – failure stress for the reinforced masonry under diagonal compression.

### 4. Results and discussions

#### 4.1. Walls subjected to compression

In the majority of models, first cracks were observed before destruction of the models. Cracks ran through joints and masonry units. In S1N series, we observed cracks on faces and local splitting of their fragments – Figure 3. There were occasional cracks on lateral surface (parallel to the masonry face). In the walls with truss from S1Zk series, we could also observe face splitting from the elements – Figure 4. Cracking in all the elements from S2StM-I and S2StM-II that were reinforced with TBM grids was similar. The first cracks developed at the extension of perpend joints or in the mid-length of masonry units. Increasing the load developed cracks and formed new ones, also along the masonry thickness. At the moment of destruction, the failure covered the whole height of the masonry. The cracks were visible not only on the model face, but also along the masonry thickness. Reinforcement was not damaged in sites where the cracks indicated crushing of masonry units. The appearance of secondary cracks demonstrated that fibres of reinforcement meshes were ruptured – Figure 5. Results for the relationship \( \sigma_y - \varepsilon_y, \sigma_y - \varepsilon_y \) and comparison of tests results are shown in Figure 6.

Figure 3. Cracks in details in the models from S1N series - without reinforcement
4.2. Walls subjected to diagonal compression

All reinforced and unreinforced test elements with one-side mortar were rapidly destroyed. It means that at the applied load, the developed cracks were not visible on the masonry surface, there were only single and not too intensive sounds of cracking. Destruction of elements consisted in losing adhesion between masonry units and mortar in bed joints, and cracking of units in the central part of the masonry. Typical cracking pattern of reinforced and unreinforced models with mortar applied on one side is illustrated in Figure 7. In reinforced models, in which mortar was applied on both sides, the form of destruction was slightly different. In the first place, cracks in masonry units were observed in the central part of the masonry. And the increased load resulted in a secondary loss in adhesion between masonry units and mortar – Figure 8.
Shear deformation in all masonry units was changing proportionally to the stress until the moment of cracking. Walls without reinforcement and wall with two-side mortar were cracked, and then destroyed. No increases in shear deformation were observed. In reinforced walls with cracks, we observed cracks developed along the diagonal. The models with truss reinforcement demonstrated the highest deformability. For walls with TBM reinforcement, we obtained the comparable values of failure stress, but considerably lower values of shear deformation because of ruptured fibres of meshes. Results for the relationship $\tau - \Theta$ and comparison of tests results are shown in Figure 9.

Figure 7. Typical forms of destruction of reinforced and unreinforced walls with mortar applied on one side: a) unreinforced units, b) units with truss reinforcement and one-side mortar, c) units with TBM – Reinforcement mesh and one-side mortar

Figure 8. Typical forms of destruction of reinforced walls with mortar applied on both sides: a) units with truss reinforcement, b) units with TBM Reinforcement mesh

Figure 9. Test results for walls subjected to diagonal compression: a) relationship stress-shear deformation in all models, b) compared values of cracking and failure stress
4.3. Discussion

For the walls under compression, reinforcement had the most positive effect on values of normal stress at which cracks were developed, in the models reinforced with truss and TBM – Reinforcement mesh and with one-side mortar – Table 3. The masonry reinforced with truss and TBM – Reinforcement mesh and with the two-side mortar exhibited the highest resistance to compression. In the unreinforced walls, cracking stress constituted ca. 79% of failure stress. The difference between cracking and failure stress dropped to 9% when reinforcement was used. For walls with TBM – Reinforcement mesh, the difference was 16% and 21%, respectively. Values of parameter $\chi_c$ were similar in all the models. Thus, the technology of mortar application seems to be negligible. The effect of technology of mortar application was more noticeable in walls under diagonal compression – Table 3. Cracks in reinforced and unreinforced models with one-side mortar were developed soon before the destruction. Two-side application of mortar resulted in some reserve of the model capacity. Differences in values of parameter $\chi_{cd}$ describing the effect of technology of placing the reinforcement, were greater compared to the walls under diagonal compression. In the walls with one-side mortar, the values of parameter $\chi_{cd}$ were lower than one. The favourable effect of the reinforcement was obtained at two-side technology of mortar application $\chi_{cd} >1.0$.

Table 3. Average values for test models under compression and diagonal compression

| Name of series          | Cracking stress, $\sigma_{cr}$ N/mm² | Failure stress, $\sigma_u$ N/mm² | $\chi_c$ | Cracking stress, $\tau_{cr}$ N/mm² | Failure stress, $\tau_u$ N/mm² | $\chi_{cd}$ |
|-------------------------|--------------------------------------|----------------------------------|----------|------------------------------------|-------------------------------|-------------|
| RL-S-N-1-6              | 2.35                                 | 2.97                             | 1        | 0.192                              | 0.196                         | 1           |
| unreinforced [7,8]      |                                      |                                  |          |                                    |                               |             |
| RL-S-Z1-1-3             | 2.85                                 | 3.12                             | 1.1      | 0.141                              | 0.157                         | 0.8         |
| one-side mortar [7,8]   |                                      |                                  |          |                                    |                               |             |
| RL-S-Z1-4-6             | --                                   | --                               | --       | 0.241                              | 0.269                         | 1.4         |
| two-side mortar [7,8]   |                                      |                                  |          |                                    |                               |             |
| RL-S-Z3-1-3             | 2.50                                 | 2.99                             | 1.0      | 0.093                              | 0.102                         | 0.5         |
| one-side mortar         |                                      |                                  |          |                                    |                               |             |
| RL-S-Z3-4-6             | 2.42                                 | 3.05                             | 1.0      | 0.237                              | 0.242                         | 1.2         |
| two-side mortar         |                                      |                                  |          |                                    |                               |             |
5. Conclusions

To sum it up, we can draw the following conclusions from the above studies. In terms of walls under compression:

- no adverse effect of the applied reinforcement was found on the behaviour of compressed walls,
- cracks in the reinforced models were observed at the level of at least 80% of maximum stress,
- walls with TBM Reinforcement mesh had the highest compressive strength in case of both-side mortar,

In terms of walls under diagonal compression:

- no adverse effect of the applied reinforcement was found on the behaviour of walls in case of one-side mortar:
  - destruction was rapid,
  - a loss in adhesion between masonry units and bed joint mortar occurred,
  - cracks in the reinforced models were observed at the level of > 90% of maximum shear stress,
- the positive effect of reinforcement was found in the models with the two-side mortar.

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