Comparison of Influence of Superficial Strengthening with FRCM System and Kind of Mortar Type on Shear Strength of Autoclaved Aerated Concrete Masonry

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Abstract. This paper describes a comparison of results from testing shear strength of autoclaved aerated concrete (AAC) walls strengthened with superficial strengthening with the results of tests of walls made of various types of joints and mortar. The initial and characteristic shear strength and the angle of internal friction were compared. The test elements were made using two types of mortars, three types of joints, and two methods of reinforcement. The models were made using masonry units in the SOLBET OPTIMAL system. SOLBET 0.1 mortar, intended for thin joints, as well as SOLBET SMART polyurethane adhesive were used. Typical joints with a width equal to the thickness of the wall, shell bedded joints and joints without mortar were made. Models with typical joints were also tested as reinforced on one and two sides with the FRCM system, using the mineral cement matrix PBO-MX GOLD MASONRY and the PBO-MESH GOLD 22/22 mesh. A total of 56 models were tested in accordance with the requirements of PN-EN 1052-3:2004. A significant influence of with superficial strengthening as well as the type of mortar and the construction of joints on the individual parameters of shear strength was demonstrated.

1. Introduction

The simplest way to increase strength of the masonry at the designing phase is to improve strength parameters of the masonry units or increase the wall thickness. This result can be also achieved by modifying mortars, joints or by placing reinforcement in bed joints. The last method means the superficial strengthening which can be usually applied to existing structures which have been damaged or which demonstrate too low load capacity when compared to new, greater load imposed due to a change in use of the construction. The effective superficial strengthening of reinforced concrete elements was verified by numerous experimental tests, whose use was codified. Also the effective superficial strengthening in masonry structures was a subject of many tests. These tests mainly referred to walls made of calcium silicate or ceramic units, predominantly to brick walls.

The tests to determine the effect of superficial strengthening on mechanical parameters of walls made of autoclaved aerated concrete units (AAC) were conducted at the Department of Building Structures at the Silesian University of Technology. This research program included the tests on the effect of superficial strengthening on compressive and tensile strength of AAC walls. The tests were performed in accordance with the standards [1, 2], and the obtained results are described in the papers [3, 4]. The final stage of testing included shear strength of the wall. The results are discussed in this paper and compared with the results obtained for the unstrengthened walls with different types of mortar and joints [5-7]. The tests were performed in accordance with the standard [8] which has been harmonised with...
Eurocode 6 [9]. The procedure A was applied to determine initial and characteristic shear strength \((f_{vo} \text{ and } f_{vok})\) of the wall and the tangent of the internal friction angle of mortar in bed joints \((0.8\tan\alpha)\).

2. Test models and research program

The test models were prepared from the same materials as the walls described in the papers [3, 4]. The applied autoclaved aerated concrete units had the following dimensions: length \(l_u = 590\) mm, width \(t_u = 180\) mm, and height \(h_u = 240\) mm. The blocks were characterized by standardized compressive strength \(f_b = 4.0\) N/mm\(^2\) and density class 600 kg/m\(^3\). They had factory-moulded tongue and groove sides. The ready-mixed system mortar SOLBET 0.1 dedicated to thin joints with compressive strength \(f_m = 6.1\) N/mm\(^2\) was used to bond masonry units. It was applied over the whole width of the wall or as two strips of 50 mm in width. The masonry units were also bonded by SOLBET SMART polyurethane adhesive applied as two strips.

Depending on the length and height of masonry units, the standard [8] defines two types of test models: type I and II. The test models were prepared as test specimens of type II and they contained two masonry units which were adequately cut to size. The test specimens, their dimensions and shapes are illustrated in Figure 1. The models were stored under laboratory conditions at +20 °C and relative humidity of 70-85%.

Side surfaces of the models were superficially strengthened after 28 days from their preparation by applying the system mortar PBO-MX GOLD MASONRY and embedding the mesh PBO-MESH GOLD 22/22. Then, the top layer of the system mortar PBO-MX GOLD MASONRY was applied.

The test specimens were marked with the capital letter S and additional capital letters defined a type of the used mortar: M, MP and P. The capital letter F described the specimens with superficial strengthening and numbers 1 and 2 defined one- or two-side strengthening. Nine test specimens were prepared for each type of the model following the standard requirements [8]. The research program for initial shear strength of the wall is presented in Table 1.

| Series code | Number of test specimens | Type of mortar and joints | Strengthening technique |
|-------------|--------------------------|---------------------------|-------------------------|
| SM          | 9                        | thin-layer joint          | -                       |
| SMP         | 9                        | shell bedded joint        | -                       |
| SP          | 9                        | polyurethane adhesive     | -                       |
| S           | 9                        | without mortar            | -                       |
| SMF1        | 9                        | thin-layer joint          | one-side                |
| SMF2        | 9                        | thin-layer joint          | two-side                |
|             |                          |                           |                         |

Table 1. The research program of the masonry initial shear strength
3. Test stand and testing technique

The tests were performed on the unstrengthened masonry models 28 days after their preparation. For the strengthened models the tests began 28 days after their strengthening. The procedure A specified in the standard [8] was used to determine the parameters. The test specimens were examined at different initial compressive stresses perpendicular to bed joint planes. All specimens were tested in a specially designed test stand placed in the testing machine (6) with the operating range of 3000 kN. A view of the test stand and the test model is shown in Figure 2. A steel frame (4) was used to impose the standard stress on bed joints in the test specimen (1) through the hydraulic cylinder (3), sheets and Teflon spacers (7). Shear load parallel to bed joints was carried through the testing machine and a hinge (5). Electro-resistant dynamometers ((2) and (8) accordingly) with 100 kN range were used to measure prestress and shearing force.

Each test series included three test specimens loaded with three different standard stress values perpendicular to the plane of bed joints. As specified in the standard [8], stress values of the masonry units with \( f_{b} < 10 \text{N/mm}^2 \) should have the following values \( f_{pi} = 0.1; 0.3; 0.5 \text{ N/mm}^2 \) and should be determined from the following relationship:

\[
 f_{pi} = \frac{F_{p,i}}{A_{hi}}, \quad \text{N/mm}^2 \quad (1)
\]

where:
- \( F_{p,i} \) – value of initial compressive load;
- \( A_{hi} \) – cross-section area of the i-th test specimen.

Compressive load \( F_{p,i} \) of the following values 5400; 16200; 27000 N was imposed to reach the recommended initial stresses for cross-section area \( A_{hi} = 36 \text{ 000 mm}^2 \) for each test specimen.

Vertical and horizontal loads, and vertical relative displacements of cut-to-size masonry units that were bonded, were recorded during the tests. The displacements were measured with two linear variable differential transducers LVDT (9) with the measuring range of 10 mm±0.002 mm. The transducers were fixed to both sides of the models. Forces and displacements were recorded using the automated stand for measurements.

The measured displacements were used to determine the greatest shear load \( F_{i,\text{max}} \), under which the rate of displacement increase was not proportional. Shear strength \( f_{voi} \) of the test specimens was determined from the relationship (2) as a ratio of load \( F_{i,\text{max}} \) and doubled area of bed face \( 2A_{hi} \).

\[
 f_{voi} = \frac{F_{i,\text{max}}}{2A_{hi}}, \quad (2)
\]

where: \( F_{i,\text{max}} \)– maximum shear strength determined for the i-th test specimen.
Figure 2. The test stand for testing the masonry initial shear strength with the test model (description in text)

Bed faces of masonry units were inspected after the test to classify the failure mechanism of the specimen as specified in the standard [8]. Shear strength values $f_{v0}$ calculated for each test specimen are illustrated on the graph as a function of initial compressive stress values $f_{pi}$ – Figure 3.
Figure 3. The rule of determining the basic parameters of the shear according to PN-EN 1052-3:2004 [8]: 1 – regression function; 2 – adjusted regression function.

The obtained results contained the least square regression line. Then, initial shear strength and internal friction angle at the intersection point between the straight line and vertical axis were determined from the equation of a straight line. Characteristic values of initial compressive strength, the tangent and the internal friction angle were determined from the following equation:

\[ f_{\text{vok}} = 0.8 f_{\text{vo}}, \text{ N/mm}^2, \]  
\[ \tan \alpha_k = 0.8 \tan \alpha, \]  
\[ \alpha_k = \arctg(0.8 \tan \alpha) \]

where:

- \( f_{\text{vo}} \) – initial shear strength of the wall;
- \( f_{\text{vok}} \) – characteristic initial shear strength of the wall;
- \( \alpha \) – internal friction angle;
- \( \alpha_k \) – characteristic value of internal friction angle.

4. Test results

Table 2 shows strength parameters of the test models with superficial strengthening and the results for unstrengthened models for comparison. For the models with one-side strengthening (SMF1 models), the initial shear strength of wall was \( f_{\text{vo}} = 0.23 \text{ N/mm}^2 \), and the corresponding characteristic strength was \( f_{\text{vok}} = 0.18 \text{ N/mm}^2 \). The internal friction angle was \( \alpha = 43^\circ \) and the characteristic value was \( \alpha_k = 37^\circ \). The characteristic tangent of an inclination angle was equal to 0.8\( \tan \alpha = 0.76 \).

For the models with two-side strengthening (SMF2 models), the initial shear strength of wall was \( f_{\text{vo}} = 0.37 \text{ N/mm}^2 \), and the corresponding characteristic strength was \( f_{\text{vok}} = 0.29 \text{ N/mm}^2 \). The internal friction angle was \( \alpha = 32^\circ \) and the characteristic value was \( \alpha_k = 26^\circ \). The characteristic tangent of an inclination angle was equal to 0.8\( \tan \alpha = 0.49 \).

For the specimens with mineral-based mortar and without any superficial strengthening (the SM and SMP series), the initial shear strength of the wall and the corresponding characteristic strength were \( f_{\text{vo}} = 0.31 \text{ N/mm}^2 \) and \( f_{\text{vok}} = 0.24 \text{ N/mm}^2 \) for the SM series models, and \( f_{\text{vo}} = 0.13 \text{ N/mm}^2 \) and \( f_{\text{vok}} = 0.11 \text{ N/mm}^2 \) for the SMP series models. For the SM models with shell bedded joints, the internal friction angle was \( \alpha = 32^\circ \), and the characteristic value was \( \alpha_k = 27^\circ \). The calculated characteristic tangent of an inclination angle was 0.8\( \tan \alpha = 0.50 \). For the SMP models with shell bedded joints, the internal friction angle was \( \alpha = 34^\circ \), the characteristic value was \( \alpha_k = 28^\circ \), and the calculated characteristic tangent of an inclination angle was equal to 0.8\( \tan \alpha = 0.54 \).
The models with shell bedded units and polyurethane adhesive had the initial shear strength equal to \( f_{vo} = 0.28 \text{ N/mm}^2 \), and the internal friction angle equal to \( \alpha = 43^\circ \). The corresponding characteristic values were \( f_{vok} = 0.11 \text{ N/mm}^2 \) and \( \alpha_k = 28^\circ \). The calculated characteristic tangent of the internal friction angle was 0.8tg\( \alpha \) = 0.43.

The models of S series without mortar and polyurethane adhesive had the value of internal friction angle equal to \( \alpha = 43^\circ \) and the corresponding characteristic value was \( \alpha_k = 36^\circ \). The characteristic tangent of the internal friction angle based on the latter value was equal to 0.8tg\( \alpha \) = 0.74.

| Table 2. Summary of the test results |
|--------------------------------------|
| Series code | \( f_{vo} \) [N/mm\(^2\)] | \( f_{vok} \) [N/mm\(^2\)] | \( \alpha \) [\(^\circ\)] | 0.8tg\( \alpha \) | \( \alpha_k \) [\(^\circ\)] |
| SM | 0.31 | 0.24 | 32 | 0.5 | 27 |
| SMP | 0.13 | 0.11 | 34 | 0.54 | 28 |
| SP | 0.28 | 0.22 | 28 | 0.43 | 23 |
| S | 0 | 0 | 43 | 0.74 | 36 |
| SMF1 | 0.23 | 0.18 | 43 | 0.76 | 37 |
| SMF2 | 0.37 | 0.29 | 32 | 0.49 | 26 |

The following equation specified in the standard [9] should be used to determine the characteristic compressive strength \( f_{vk,EC6} \):

\[
f_{vk,EC6} = 0.5 f_{vko,EC6} + 0.4 \sigma_d + 0.5 f_{vko,EC6} + 0.8 \tan \alpha_{EC6} \sigma_d
\]  
\[
(6)
\]

For the walls with shell bedded joints, where the minimum thickness of each strip \( g \) is 30 mm, the equation below is applied:

\[
f_{vk,EC6} = \sum_{l} g f_{vk,EC6} + 0.4 \sigma_d = \sum_{l} g f_{vk,EC6} + 0.8 \tan \alpha_{EC6} \sigma_d
\]  
\[
(7)
\]

However, shear strength cannot exceed

\[
f_{vk,EC6} = 0.045 f_b
\]  
\[
(8)
\]

or

\[
f_{vk,EC6} = 0.7 \text{ of the boundary value specified in Table 3.1 in the standard [9].}
\]

Table 3 and Figure 4 present the test results and the determined characteristic values of shear strength. These values were compared with parameters specified in the standard EC6 [9].
The A-type failure was observed in all specimens (except for the S series specimens) which consisted in shearing mortar in place of its contact with the masonry units. Consequently, mortar was found on both surface areas of the test specimens (Figure 5a) or only on one surface area (Figure 5b). All strengthened surfaces of the test specimens of the SMF1 and SMF2 series showed cracking of the cement matrix (Figure 5c) while the mesh fibres were not broken.

![Image of test specimens](image)

**Figure 5.** A view of models after tests. Models of series: a) SMF1, b) SM, c) SM F2

**Table 3.** Comparison of the test results

| Series code | $f_{vok}$ [N/mm$^2$] | $f_{vok,EC6}$ [N/mm$^2$] | $f_{vok} / f_{vok,EC6}$ | $0.8tg\alpha$ | $0.8tg\alpha_{EC6}$ | $0.8tg\alpha_{EC6}$ / $0.8tg\alpha$ |
|-------------|-----------------|-----------------|-----------------|------------|-----------------|-----------------|
| SM          | 0.24            | 0.25            | 0.96            | 0.5        | 1.25            | 1.35            |
| SMP         | 0.11            | 0.44            | 0.44            | 0.54       | 1.08            | 1.85            |
| SP          | 0.22            | 0.88            | 0.88            | 0.43       | 1.80            | 1.90            |
| S           | 0               | 0               | 0               | 0.74       | 1.90            | 1.90            |
| SMF1        | 0.18            | 0.72            | 0.72            | 0.76       | 1.90            | 1.90            |
| SMF2        | 0.29            | 1.16            | 1.16            | 0.49       | 1.23            | 1.23            |

**Figure 4.** Comparison of test results to the equation proposed in the EC6 [9] (according to the formula (6) and (7))
The initial shear strength determined from the tests was greater than the standard value by 16% only when joint width in the test specimens was equal to thickness of the wall with two-side strengthening (the test specimens of SMF2 series). For the wall with a joint width equal to thickness of the one-side strengthened wall (SMF1 series) or the unstrengthened wall (SM series), the determined values were lower than the standard ones by 28% and 4% respectively. Also, the values for the shell bedded joints and the joint with polyurethane adhesive layer were lower than the standard values by 66% and 12% respectively. More satisfactory results were found for the internal friction angle $0.8\tan \alpha$ of mortar in the bed joint as the values determined for all test series were higher than the standard values $0.8\tan \alpha = 0.4$. The biggest differences at the level of 90% and 85% were observed for the models with joint width equal to thickness of the wall with one-side strengthening (the test specimens of SMF1 series) and for the models without mortar (the test specimens of S series). For the walls with a joint width equal to thickness of the two-side strengthened wall (SMF2) and without strengthening (SM), the determined values increased by 23% 25% respectively. An increase by 35% was found in the models with the mineral-based shell bedded joint. The models with the joint with polyurethane adhesive layer demonstrated the lowest increase in friction coefficient at the level of 8%.

5. Conclusions

The following conclusions were based on the obtained results:

- the initial shear strength of the masonry models with mineral-based mortar was $f_{\text{vo}} = 0.13 \div 0.31$ N/mm$^2$, and the resulting characteristic strength was determined as $f_{\text{vok}} = 0.11 \div 0.24$ N/mm$^2$,
- the initial shear strength of the masonry models with mineral-based mortar and one- or two-side strengthening was $f_{\text{o}} = 0.23$ N/mm$^2$ and 0.37 N/mm$^2$. The resulting characteristic strength values were $f_{\text{vok}} = 0.18$ N/mm$^2$ and $f_{\text{vok}} = 0.29$ N/mm$^2$ respectively,
- the initial shear strength of the models with polyurethane adhesive was $f_{\text{vo}} = 0.28$ N/mm$^2$, and the corresponding characteristic strength was $f_{\text{vok}} = 0.22$ N/mm$^2$,
- the internal friction angle and the characteristic value for walls with mineral-based mortar were $\alpha = 32^\circ \div 34^\circ$ $\alpha_k = 27^\circ \div 28^\circ$. The angle values were $\alpha = 43^\circ$ and $\alpha_k = 37^\circ$ for the one-side strengthened models, and $\alpha = 32^\circ$ and $\alpha_k = 26^\circ$ for two-side strengthened models,
- the internal friction angle and the characteristic value for the masonry with joints and polyurethane adhesive were $\alpha = 28^\circ$ and $\alpha_k = 23^\circ$, and for the masonry without mortar, these values were $\alpha = 43^\circ$ and $\alpha_k = 36^\circ$,
- the tangent of the internal friction angle in the walls with mineral-based mortar was $0.8\tan \alpha = 0.5 \div 0.4$, and in the walls with superficial strengthening was $0.8\tan \alpha = 0.49 \div 0.76$. The tangent values of the internal friction angle in the walls with polyurethane adhesive and without mortar were $0.8\tan \alpha = 0.43$ and $0.8\tan \alpha = 0.74$ respectively,
- all test specimens, except for the walls without mortar, were damaged as the effect of shearing at the interface between mortar and the masonry unit (the A-type failure).

The comparison of the test results and the equations specified in EC6 led to the following conclusions:

- the initial characteristic shear strength of the wall with mineral-based mortar and polyurethane adhesive was lower by $4 \div 66\%$ than the standard value of $f_{\text{vok, EC}} = 0.25$ N/mm$^2$.
- Superficial strengthening on one or both sides of the model resulted in initial compressive strength of the wall which was lower by 28% and higher by 16% than the standard value,
- the internal friction angle in the joint $0.8\tan \alpha$ was greater in all the model series than the standard value $0.8\tan \alpha = 0.4$. The highest increase was found in the one-side strengthened models (90%) and the models without mortar (85%), and the lowest increase (8%) was observed in the models with polyurethane adhesive. The values in other models with mineral-based mortar increased by 35% (the models with shell bedded joints), by 25% (the models with the joint width equal to the wall thickness), and by 23% (the models with two-side strengthening),
- when compared to the unstrengthened models, superficial strengthening mitigated the behaviour of the tests models,
- the determined values of shear strength were higher than the standard values obtained from the equation (6) which took into account the standard strength reduction by 50%.
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