Influence of Grid Reinforcement Placed In Masonry Bed Joints on Its Flexural Strength

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Abstract. The paper presents the test results of the flexural strength of masonry when plane of failure is perpendicular to the bed joints. Comparison tests of unreinforced specimens and specimens reinforced with steel wire, glass and basalt fibre grids applied in masonry bed joints showed the higher flexural strength and crack resistance of masonry reinforced in this manner and so loaded. Reinforced masonry exposed plastic character after cracking allow for large horizontal displacements and transfer the considerable loads perpendicular to their surface. The strengthening of masonry was observed in most tests of reinforced specimens leading to occurrence of the maximum load in after cracking phase.

1. Introduction

There are two cases of masonry flexural failure, according to PN-EN 1996-1-1 [1] standard, considering the orientation of bending moment plane perpendicular to the surface of the wall. In first case the plane of failure is parallel to the bed joints plane. The bond strength between masonry units and mortar is generally lower than the tensile strength of masonry units. That is why in this situation plane of weakness goes through the bed joints. The characteristic flexural strength of masonry is then marked by $f_{xk1}$ symbol. In the second case plane of failure is perpendicular to the bed joints. Failure of the wall then depend on flexural strength of masonry units and the plane of failure goes through the head joints and masonry units (figure 1a) or the stepped crack can occur which runs only through the bed and head joints (figure 1b) and for masonry with unfilled head joints failure is governed mainly by shear (torsional) strength of bed joints. Mixed failure mechanism is also highly probable. In the latter case, according to [1] standard, the characteristic flexural strength of masonry is marked by $f_{xk2}$ symbol.

Increasing of masonry flexural strength, when the plane of failure is perpendicular to the bed joints, is possible by placing the reinforcement in bed joints. The PN-EN 1996-1-1 standard [1] introduce even the concept of apparent design flexural strength of masonry having the plane of failure perpendicular to the bed joints $f_{xk2,app}$, which is determined by comparing the design capacity of unreinforced cross section of $f_{xk2,app}$ strength masonry with capacity of reinforced masonry.

The paper presents the results of influence of application in masonry bed joints of grid reinforcement made of various materials on the flexural strength of masonry when plane of failure is perpendicular to the bed joints and the effect of this type of reinforcement on the value of load perpendicular to the surface of masonry inducing cracks. During the tests the horizontal displacements (deflection) of unreinforced and reinforced masonry were measured as well.
2. Specimens and testing procedure
Masonry specimens were made of autoclaved aerated concrete (AAC) masonry units SOLBET Optimal with mean density 600 kg/m$^3$, equipped with a gripholes and tongues and grooves on the head faces. According to manufacturer’s declaration nominal width of masonry units was 180 mm, height 240 mm and length 590 mm with declared dimensional tolerances equal ±1.5 mm for length and width and ±1.0 mm for height. AAC blocks was masonry units category I, according to standard [1], and had declared 3.0 N/mm$^2$ compressive strength. Laboratory tests published in article [2] showed that the normalized mean compressive strength of AAC blocks $f_{b}$, determined per PN-EN 772-1 [3] standard on cubic samples cut from whole blocks, was 4.04-4.10 N/mm$^2$ depending on load direction.

Declared by manufacturer the flexural strength of masonry made of used AAC blocks for plane of weakness parallel to the bed joints was 0.105 N/mm$^2$ and not less than 0.075 N/mm$^2$ when failure occurs in plane perpendicular to the bed joints of masonry with unfilled head joints.

Masonry specimens for flexural strength tests were made using the masonry mortar class M5 with white cement for masonry structures with thin joints SOLBET 01. According to the laboratory tests [2], determined per PN-EN 1015-11 [4], mean flexural strength of mortar was equal to 2.0 N/mm$^2$ and mean compressive strength was 6.1 N/mm$^2$.

Three types of grids were used as reinforcement placed in masonry bed joints:
- welded steel Armanet® with square mesh 12.7 × 12.7 mm, single wire diameter 1.05 mm (figure 2a), corrosion protected with a zinc coating in amount of not less than 350 g/m$^2$. According to the manufacturer’s declaration tensile strength of single wire was 350 N.
- glass fibers having warp composed of three threads and single strand of weft (figure 2b). Distance between the middle strands of warp was ca. 13 mm and ca. 9 mm between weft strands. Grammage of impregnated grid was 335 ± 30 g/m$^2$ (according to the manufacturer’s information). Declared tensile strength of 5 cm wide strip of grid was not less than 4000 N in case of tension in warp direction and 3000 N in weft direction. Grid was alkali-resistant and resistant to putrefaction.
- basalt fibers with square mesh 30 × 30 mm, grammage of 260 ± 10 g/m$^2$, composed of single strand of warp and quadruple weft thread (figure 2c). Declared tensile strength in both orthogonal directions was 50000 N/m, elongation at fracture 2.5 ± 1%, density of fibers 2.67 ± 5% g/cm$^3$ and melting temperature 1350 ± 100°C.
Figure 2. Grids used as reinforcement in the masonry bed joints and made of: a) galvanized steel wire, b) glass fibers, c) basalt fibers

Shape and overall dimensions of the masonry specimens were determined according to requirements of PN-EN 1052-2 standard [5] when plane of failure is perpendicular to the bed joints. Figure 3 shows nominal dimensions of tested masonry specimens assuming that thickness of bed joints and unfilled head joints is equal 3 mm. PN-EN 1052-2 test method is usually called the method of four load points. The specimen is simply supported along two linear supports distant about 50 mm from vertical edges of masonry (the dotted line in figure 3). Loading was applied to the specimen along two lines at the same distances from the supports lines (the wavy line in figure 3), so as to between loading lines there was one head joint in each layer of masonry. In case of described tests distance between supports was \( l_1 = 1375 \text{ mm} \), and distance between loading lines was \( l_2 = 750 \text{ mm} \), therefore the ratio \( l_2/l_1 \) was in the range from 0.4 to 0.6 required by the standard [5].

Figure 3. Masonry specimens used in tests

A total of 24 specimens tests were carried out. Six unreinforced masonry and three series of six specimens with each type of grid reinforcement were examined. Reinforcement was placed in each masonry bed joint and grids were continuous. In cross section of each bed joint there were 13 steel wires, 12 triple glass fibers threads and 6 basalt fibers strands. Effective width of steel and glass fibers grid was therefore equal to 155 mm and width of basalt fibers grid was 145 mm. Declared tensile
The strength of single grid reinforcement in direction parallel to the masonry bed joints was 4.55 kN for steel reinforcement, 11.6 kN and 7.75 kN for glass and basalt fibers grid respectively.

Unreinforced masonry specimens had X2N-i marks, specimens with steel wire grid had X2S-i symbols, masonry with glass fibers reinforcement had X2G-i marks and basalt fibers reinforced specimens was labelled by X2B-i marks, where i is the number of subsequent specimen, i = 1 … 6.

The tests were carried out in especially designed steel test stand corresponding to the requirements of the PN-EN 1052-2 standard [5] whose sketch is shown in figure 4. Linear supports and members used for load transfer to the specimen consist of several parts to ensure uniform load distribution. Mentioned load transmitting members were pivotally connected with the cross beams loaded by F force. The specimens were tested in a vertical position to avoid the influence of self-weight on the values of normal stresses in masonry bent cross section. Force F was carried out by the hydraulic jack with an appropriate range.

![Figure 4. Test stand](image)

Apart from the force F measurement the horizontal displacements (deflection) were recorded at two points located in the middle of the span in two inner layers of masonry (figure 3). The displacement transducers with the range of 20 mm had contact with compressed face of specimens.
3. Results of the tests

Mean and characteristic flexural strength of the tested masonry were determined according to guidelines on PN-EN 1052-2 standard [5]. The table 1 contains the individual values and characteristic value of flexural strength of unreinforced and reinforced specimens for plane of failure perpendicular to the masonry bed joints.

Table 1. Results of flexural masonry strength tests

| Specimen | The maximum force $F$, kN | Flexural strength $f_x$, N/mm² | Characteristic flexural strength $f_{xk}$, N/mm² |
|-----------|---------------------------|-------------------------------|-----------------------------------|
| **Unreinforced masonry** | | | |
| X2N-1     | 4.29                      | 0.13                          | 0.07                              |
| X2N-2     | 3.68                      | 0.11                          |                                   |
| X2N-3     | 3.69                      | 0.11                          |                                   |
| X2N-4     | 2.68                      | 0.08                          |                                   |
| X2N-5     | 3.14                      | 0.09                          |                                   |
| X2N-6     | 3.73                      | 0.11                          |                                   |
| **Masonry with steel wire grid reinforcement** | | | |
| X2S-1     | 8.93                      | 0.27                          |                                   |
| X2S-2     | 6.39                      | 0.19                          |                                   |
| X2S-3     | 8.37                      | 0.25                          | 0.14                              |
| X2S-4     | 6.85                      | 0.21                          |                                   |
| X2S-5     | 11.3                      | 0.34                          |                                   |
| X2S-6     | 6.08                      | 0.18                          |                                   |
| **Masonry with glass fibers grid reinforcement** | | | |
| X2G-1     | 8.93                      | 0.27                          |                                   |
| X2G-2     | 7.05                      | 0.21                          |                                   |
| X2G-3     | 7.97                      | 0.24                          | 0.19                              |
| X2G-4     | 9.92                      | 0.30                          |                                   |
| X2G-5     | 8.06                      | 0.24                          |                                   |
| X2G-6     | 8.07                      | 0.24                          |                                   |
| **Masonry with basalt fibers grid reinforcement** | | | |
| X2B-1     | 10.2                      | 0.31                          |                                   |
| X2B-2     | 8.61                      | 0.26                          |                                   |
| X2B-3     | 7.75                      | 0.23                          |                                   |
| X2B-4     | 8.99                      | 0.27                          |                                   |
| X2B-5     | 8.76                      | 0.26                          |                                   |
| X2B-6     | 7.30                      | 0.22                          |                                   |

Figure 5 shows the characteristic manner of specimens cracking. For most unreinforced masonry cracks go through head and bed joints (figure 5a) except specimen X2N-6 where vertical plane of failure runs through head joints and masonry units (figure 5b). In case of all reinforced specimens failure lies in formation of the crack in single vertical section which goes through head joints and masonry units (figure 5c) or cracks in many sections of these kind (figure 5d).

In figure 6 there are graphs of the relationship between mean horizontal displacements of masonry $w$ and load $F$. In case of four unreinforced specimens (X2N series) the mode of failure was brittle, that is after the peak load cracking has occurred and rapid loss of force with little deflection of masonry (figure 6a). However, two unreinforced specimens had a specific plastic behaviour, which means that after cracking the masonry was able to transfer a relatively high force with substantial horizontal displacements. In case of these two specimens the maximum load value was obtained not at the
moment of cracking but after the masonry hardening with large deflections. This peculiar nature of failure could be caused by jamming the mutual rotating blocks because of the shape of head faces of masonry units equipped with tongues and grooves.

Figure 5. Flexural failure of masonry specimens with the cracks which goes through: a) head and bed joints of unreinforced masonry; b) head joints and masonry units of unreinforced masonry; c) one section of reinforced masonry; d) many sections of reinforced masonry

All specimens with steel reinforcement demonstrated ductile nature of failure (X2S series). After the cracking the horizontal displacements of masonry were large and the carried load was still high (figure 6b). Mean value of $F$ force for horizontal deflection ca. 20 mm was higher than mean failure load for unreinforced specimens. In case of four specimens X2S series the maximum load was also the load causing cracks. For two specimens with steel reinforcement the hardening after cracking was sufficiently high that the maximum force was recorded in the plastic phase.

Relationships between force $F$ and displacement $w$ for specimens with glass (X2G series) and basalt (X2B series) fibers grids were ductile in nature (figure 6c and figure 6d). As previously the
large displacements of masonry were observed with the accompanying still relatively high load capacity. In a few cases, however, there were bigger drops in masonry capacity and with smaller displacements compared to the specimens with steel reinforcement (figure 6b vide figure 6c and figure 6d). Different character also had the masonry hardening in after cracking phase. In all tests of the specimens X2G and X2B series the force at the moment of cracking was not the ultimate load. The maximum value of $F$ force was obtained in the hardening stage after masonry cracking.

![Figure 6. The relationship between deflection w and F force in case of the masonry: a) without reinforcement; b) with steel fibers grids; c) with glass fibers reinforcement, d) with basalt fibers grids](image)

### 4. Synthesis of the tests results

Characteristic masonry flexural strength when the plane of failure is perpendicular to the bed joints for each tested series and ratio of characteristic flexural strengths of reinforced specimens to unreinforced masonry are summarized in table 2.

| Specimens       | Characteristic flexural strength $f_{xk2}$, N/mm² | $f_{xk2(S,G,B)}/f_{xk2,N}$ |
|-----------------|--------------------------------------------------|-----------------------------|
| X2N – unreinforced | 0.07                                             | -                           |
| X2S – with steel wire grids | 0.14                                           | 2.00                        |
| X2G – with glass fibers grids | 0.19                                           | 2.70                        |
| X2B – with basalt fibers grids | 0.20                                           | 2.86                        |
The largest increase of flexural strength compared to the unreinforced masonry was obtained for specimens with basalt fibers grids and the smallest for masonry with steel reinforcement while the highest declared tensile strength had glass fibers grids. The increase in flexural strength of masonry was therefore not proportional to the tensile strength of used reinforcement. Explanation of this phenomenon will require the execution of the fibers tensile tests to determine the reinforcement $\sigma$-$\varepsilon$ relationship and conduction on this basis the strain and stress analysis in bent reinforced masonry cross section.

Figure 7 shows the comparison of relationships between force $F$ and horizontal displacement $w$ for unreinforced masonry (grey lines) and reinforced (black lines) with steel wire grids (figure 7a) and basalt fibers grids (figure 7b). In graphs can be seen the higher capacity and ductile nature of $F$-$w$ relationships of reinforced specimens compared with unreinforced masonry and brittle failure of the most of specimens without reinforcement.

![Figure 7. Comparison of the horizontal displacements $w$ dependent on the $F$ force obtained for unreinforced specimens (grey lines) and reinforced specimens (black lines) with: a) steel wire grids; b) basalt fibers grids](image)

Table 3 contains the mean values of cracking forces $F_{cr}$ followed usually by drop of load capacity and increase of displacements. In case of unreinforced specimens (X2N series) and masonry with steel wire grid reinforcement (X2S series) the cracking force was the ultimate load, unlike in the specimens with glass (X2G) and basalt (X2B) fibers grid reinforcement.

| Specimens                  | Mean cracking force $F_{cr,mv}$, kN | Standard deviation of $F_{cr}$ force $S_{Fcr}$, kN | Variability index of $F_{cr}$ force $V_{Fcr}$, % | $F_{cr,mv,S,G,B}/F_{cr,mv,N}$ |
|---------------------------|-----------------------------------|---------------------------------------------------|-----------------------------------------------|-------------------------------|
| X2N – unreinforced        | 3.69                              | 0.38                                              | 10.2                                          | -                             |
| X2S – with steel wire grids | 7.78                              | 2.19                                              | 28.2                                          | 2.11                          |
| X2G – with glass fibers grids | 6.63                              | 0.82                                              | 12.4                                          | 1.80                          |
| X2B – with basalt fibers grids | 6.93                              | 1.08                                              | 15.6                                          | 1.88                          |

Comparing mean values of cracking forces obtained for reinforced and unreinforced specimens (table 3) can be seen that reinforcement placed in the bed joints of masonry gives a significant increase of cracking resistance when plane of masonry failure is perpendicular to the bed joints. The biggest increase of cracking force in relation to the load causing cracks of unreinforced masonry was observed.
for specimens with steel wire grids reinforcement, although in this case the cracking force variability index was significantly higher than in other tested series.

5. Conclusions
Based on test results of flexural strength of unreinforced and reinforced masonry having the plain of failure perpendicular to the bed joints for the above-described types of reinforcement placed in bed joints, mortar and masonry units it can be concluded that the:

- characteristic flexural strength of reinforced masonry, determined according to PN-EN 1052-2 [5], was at least twice as high as the characteristic strength of unreinforced masonry;
- force that causes cracking of reinforced masonry was higher than in the case of unreinforced masonry; the ratio of mean value of cracking force obtained for reinforced masonry to mean cracking force from test of unreinforced masonry was not less than 1.80;
- maximum horizontal displacements (deflections) of reinforced masonry were larger than in most of the unreinforced masonry; the application of reinforcement in masonry bed joints allowed to carry fairly high load after cracking and for large horizontal displacements (ductile nature of reinforced masonry); in case of most of the reinforced masonry the ultimate load was achieved in the phase of masonry plastic hardening after cracking.

References
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[3] PN-EN 772-1:2011 Methods of test for masonry units. Part 1: Determination of compressive strength.
[4] PN-EN 1015-11:2001/A1:2007 Methods of test for mortar for masonry. Part 11: Determination of flexural and compressive strength of hardened mortar.
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