A study of bearing capacity of reinforced masonry beams with GFRP reinforcement

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Abstract. This article presents the results of experimental researches of bearing capacity and deformability of reinforced masonry beams with combined reinforcement. This study was carried out in the zone of maximum bending moment. The reinforcement A400C and A1000 were used for experimental samples. The combined action of ceramic masonry and reinforcement was ensured at the expense of a cement-sand grout in the joints of masonry and vertical reinforcing meshes in support zones of beams, which were welded to angle bars. Besides that, there was carried out a comparison of the results of experimental researches with calculated values by the active standards of Ukraine. This comparison permits to determine the expediency of the use of the existing design procedure of bearing capacity of reinforced masonry structures with combined double reinforcement. Finally, this scientific work has also presented the conclusions about the possibility of the efficient design of reinforced masonry structures in the effective area of normal forces.

1. Introduction

The masonry structures are widely used in civil and industrial building construction. These structures take a load from the dead weight, from ceilings, and from wind. Moreover, they execute the heat-insulating and soundproofing properties. The cost of masonry structures (foundations, walls) is 15…30 % of the total cost of the edifice, but their weight is equal to 60 % (approximately) from the weight of the edifice [1].

The reinforced masonry structures are used during the erection of foundations, outer and inner walls of buildings, ceilings, arches, chimneys, bridges, sewers, water towers, elevators, etc. (fig. 1, 2) [2]. The elements of masonry and reinforced masonry structures execute two functions: protective (these structures divide two environments with different physical properties) and bearing (they take and pass a load, which appears from operational factors (dead weight, payload, a change of temperature). The reinforced masonry structures must correspond to the operational requirements of bearing capacity, stiffness, life duration, reliability, reparability, and other properties, which will determine the quality and suitability of structure to the exploitation.
The reinforced masonry structures are widely used not only in Ukraine but and in Europe since these structures have enough bearing capacity and deformability, they are environmentally friendly and simple in mounting [3 - 5].

However, now, reinforced masonry structures with additional longitudinal reinforcement and monolithic reinforced concrete insertions are widely used (complex structures). These solutions are necessary in cases of [6, 7]:

- an increase bearing capacity of structures, when the tensile loads appear in the cross-sections and these loads exceed the design tensile strength of masonry;
- the use of flexible elements, if their flexibility is equal more than 15;
- an application in thin walls and partitions for the increase of their firmness and bearing capacity during the action of lateral loads;
- the use in walls and columns for the increase of masonry rigidity, fracture strength, and seismic stability.

Moreover, there is recommended to use a netted reinforcement for the ensuring of better combined action of masonry with longitudinal reinforcement or reinforced concrete [8, 9].

This scientific work is devoted a study of reinforced masonry beams with combined reinforcement, in which are used reinforcement rods A400C and A1000C in a lower tensile zone. This reinforcement was arranged in the extreme borders of the cross-section.

2. Materials and methods

The four reinforced masonry beams with combined reinforcement (we used reinforcement rods A400C and A1000) and two reinforced masonry beams (with usual reinforcement by reinforcement rod A400C in the tensile zone) were designed, produced, and experimentally investigated. The cross-section of all beams was 140 x 250 mm. The length of these structures was 2300 mm and the design span was 2000 mm [1].

The construction of experimental samples is shown in fig. 3.

It should be noted that experimental samples of reinforced masonry beams have differed reinforcement in the tensile zone:

- beams B-1 – one reinforcement bar Ø8 mm A1000 and one reinforcement bar Ø10 mm A400C;
- beams B-2 - one reinforcement bar Ø10 mm A1000 and one reinforcement bar Ø8 mm A400C;
- beams B-3 were produced without combined reinforcement with the purpose of the comparison with the beams with combined reinforcement. However, the beams B-3 were reinforced by two reinforcement bars Ø10 mm A400C.

The combined reinforcement of reinforcement bars A400C and A1000 were used in the tensile zone of the beams B-1 and B-2. The adhesion of reinforcement and masonry was ensured using thick calking by cement-sand grout.
Figure 3. The cross-section of the investigated reinforced masonry beams

The mesh of wire was arranged in a zone of action of maximum shears. The diameter of the wire was 5 mm A240C. The size of the cell was 50 x 50 mm. The length of the mesh was 1/3 span of beams.

The feature of the production of experimental samples with combined reinforcement consists that the structure of beams was manufactured in the horizontal position in two stages. The experimental samples of beams are two horizontal rows of brick that are produced by means of layerwise laying.

Firstly, we put in the first row of brick. The length of the first row was 2300 mm and the medium thickness of the joints was 10 mm. After that, we put on the layer of the mortar, which was produced in accordance with the requirements [10], and then we arranged the reinforcement in tensile and compressed zones of beams with adherence of the height of the protective layer. Afterward, we located the reinforcement of support sections in the zone of action of maximum shears. For that, we used the reinforcing meshes of reinforcement bars Ø5 mm A240C with cells 50 x 50 mm. Next, we put on the second row of brick on a cement-sand grout. The medium thickness of the joints was 10 mm. The joints between bricks filled up by a mortar on 100 %.

The combined action of reinforcement and brick masonry was ensured using the insert of reinforcement on cement-sand grout (the grade of this mortar was M150). This action was ensured good adhesion of reinforcement and masonry. The arrangement of all elements of structures was executed under the level to ensure the straightness of structure.

In addition to the production of experimental samples, we produced prisms (the cross-section of prisms was 120 x 145 mm and length of prisms was 250 mm). Manufactured experimental samples and prisms were held by the temperature 20°C and relative humidity 50…70 %. This action provided the growth of designed strength during 28 days.

After 28 days, the experimental beams were set up on the test bench strictly vertically by means of the level tube. After that, we plastered and fixed holders for microindicators with a base that was equal to 150 to 200 mm. The microindicators have measured the deformations of brick in the zone of pure bending.

The experimental samples of the reinforcement rod were produced for the purpose of determination of the physical-mechanical properties of longitudinal reinforcement, which was located in the tensile zone. The test was carried out stretching method of samples on the hydraulic tensile-testing machine with a simultaneous record of the data diagram of the tension of the reinforcement bar. The resistance strain gages were glued on experimental bars in places of the cavity. The deformations under the action of loading on the samples were measured using these devices. The strain-loading diagrams in reinforcement from the load for experimental samples of reinforcement bars A400C and A1000 are shown in fig. 4.

The characteristics of materials for experimental samples in accordance with building standards [11 - 13] are shown in table 1.
Figure 4. The diagrams of deformation from loading for reinforcement bars A400C and A1000

Table 1. The characteristics of materials for experimental samples

| The type of beam                                      | B-1 | B-2 | B-3 |
|------------------------------------------------------|-----|-----|-----|
| Geometrical parameters of cross-section              |     |     |     |
| b, [mm]                                              | 140 | 140 | 140 |
| h, [mm]                                              | 250 | 250 | 250 |
| A, [cm²]                                             | 350.0 | 350.0 | 350.0 |
| Ceramic blocks                                       |     |     |     |
| $f_c$, [MPa]                                         | 7.29 | 7.29 | 6.43 |
| $f_{skv}$, [MPa]                                     | 0.9 | 0.9 | 0.8 |
| $E_{cm}$x10³, [MPa]                                  | 4.3 | 4.3 | 4.3 |
| Reinforcement rod of the tensile zone                |     |     |     |
| $d_s$, [mm]                                          | Ø8  | Ø10 | Ø8  |
| $f_{yk}$, [MPa]                                      | 1080 | 510 | 510 |
| $A_s$, [cm²]                                         | 0.503 | 0.785 | 0.503 |
| $E_s$x10⁵, [MPa]                                     | 1.85 | 2   | 2.85 |
| Class                                                | A1000 | A400C | A400C |
| Reinforcement rod of the compressive zone            |     |     |     |
| $d_s'$, [mm]                                         | Ø12 | Ø12 | Ø12 |
| $f_{yk}'$, [MPa]                                     | 510 | 510 | 510 |
| $A_s'$, [cm²]                                        | 1.13 | 1.13 | 1.13 |
| $E_s'$x10⁵, [MPa]                                    | 2   | 2   | 2   |
| Class                                                | A400C | A400C | A400C |
| Cross reinforcement                                  |     |     |     |
| $d_s$, [mm]                                          | Ø5  | Ø5  | Ø5  |
| $f_{yd}'$, [MPa]                                     | 370 | 370 | 370 |
| $A_s'$, [cm²]                                        | 0.126 | 0.126 | 0.126 |
| $E_s'$x10⁵, [MPa]                                    | 1.7 | 1.7 | 1.7 |
| Class                                                | A240C | A240C | A240C |

The study of experimental beams (the calculated span was 2000 mm) was carried out using the test bench. The loading was created by means of hydraulic jack with power 1000 N that was set up on the distributive cross-arm. The effort was applied to the upper border of beams. This effort was divided into two concentrated forces, which were applied symmetrically relative to the middle of the experimental beam. The distance from the applied force to support was equal to 650 mm.
During the test, the load for beams was carried out with step, which was similar to 10% from breaking load with the exposure 30 minutes on every stage. After the exposure of the load, we took a reading of all microindicators and deflection indicators, and also we fixed the creation of cracks and, of course, a width of the opening and development of cracks. The value of loading was controlled using standard pressure gage that was calibrated together with hydraulic pumping plant and jack, and also by the value of support reactions, which were fixed by two proving rings that were simultaneously fixed and movable supports. In hinged movable support, the supporting part was executed as a flat surface. At the same time, in the hinged fixed support, the supporting part of the proving ring was executed as cylindrical surfaces with a radius ring of the dynamometer.

The deformations were fixed using the microindicators that were set up with the base 200 mm. The division value of microindicators was 0.001 mm. All deformations were measured in the zone of pure bending. The width of the cracks opening and also the height of cracks were determined at every stage of loading and were measured using microscope МПБ-2М with division loading 0.005 mm.

The studies were carried out to an appearance of the yielding flow in the high-strength reinforcement or the destruction of the experimental sample. It permitted completely to use experimental samples.

3. Results and discussions
The executed experimental studies of reinforced masonry beams permitted to determine the features of their work.

On the first stage, the work of beams (to the moment of formation cracks in masonry) we observed predominantly elastic deformations.

Table 2 summarizes the maximum values of tensile and compressive deformations of longitudinal and transverse reinforcements along the height of beam’s cross-section in the zone of the maximum moment, and also the value of the deflections to moment of the formation cracks that were obtained during the test studies of experimental samples.

| Type of beams | $M$, [kN·m] | $\varepsilon_{eA_{400}} \cdot 10^5$ | $\varepsilon_{eA_{1000}} \cdot 10^5$ | $\varepsilon_\gamma \cdot 10^5$ | $f_{max}$ [mm] |
|---------------|--------------|-----------------|-------------------|-----------------|----------------|
| B-1           | 1.01         | 77              | 79                | 55              | 2.3            |
| B-2           | 1.06         | 88              | 92                | 68              | 2.9            |
| B-3           | 0.96         | 67              | -                 | 47              | 1.4            |

At the stage to the formation of cracks, the deformations of reinforcement and masonry of all experimental samples did not differ, because typical cracks for the loss of reinforcement adhesion were not observed, which permitted to draw a conclusion about that the reinforcement was deformed uniformly along its full length.

It should be noted that the tensile and compressive deformations of masonry in the zone of normal sections were distributed along the height of elements in accordance with flat cross-section hypothesis and these deformations arranged along the length of shear span according to the bending moment diagram.

The increase of loading conducted an appearance in tensile reinforcement inelastic deformations and the stress in the tensile zone of beams reached the tensile strength of masonry $f_{xk1}$. The next increase of loading on the beam conducted the appearance of cracks that was evidenced about the beginning of the second stage of deflected mode.

There was typical that the cracks in beams with the higher reinforcement percentage by high-strength reinforcement A1000 were formed later. The riffled reinforcement bar was deformed evenly according to the bending moment diagram.

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The most deflections, till the creation of the cracks, were fixed in the second experimental sample B-2, where was designed high-strength reinforcement A1000 with the highest reinforcement percentage. The
least deflections until the creation of the cracks were identified in experimental sample B-3, where high-strength reinforcement was absent.

In such a way, at the stage from the beginning of loading till the appearance of normal cracks, the reinforced masonry beams with combined reinforcement worked jointly as the monolithic cross-section.

When the normal cracks appeared, the homogeneity of masonry disturbed and the deflected mode changed along the span of beams. The deflected mode of bricks and joints in normal sections with cracks and between these cracks was different from one another.

The tensile and compressive deformations of masonry in sections between cracks were distributed to the linear law along the full height with maximum values near the tensile and compressive sides. Besides that, the tensile and compressive deformations of masonry in section with cracks were also distributed to the linear law, but not along the full height, yet only to the upper point of cracks in the tensile zone.

The most values of deformations for compressive and tensile zones of experimental samples, deflections of beams, deformations of tensile reinforcement till the moment of limit loading are presented in table 3.

| The type of beams | 0.7M_{max}, [kN · m] | \( \varepsilon_{A400} \times 10^4 \) | \( \varepsilon_{A1000} \times 10^4 \) | \( \varepsilon_{c} \times 10^4 \) | \( f_{max}, [\text{mm}] \) |
|------------------|----------------------|-----------------|-----------------|-----------------|-----------------|
| B-1              | 14.5                 | 317             | 360             | 127             | 10.7            |
| B-2              | 17.23                | 338             | 378             | 145             | 11.1            |
| B-3              | 11.94                | 187             | -               | 87              | 9.1             |

It should be noted that the beginning of the yielding flow for reinforcement A400C was happening under the achievement of the values of relative deformations \( \varepsilon_{c, A400C} = 255 \times 10^{-5} \), and the yielding flow for reinforcement A1000 came under the values of relative deformations \( \varepsilon_{c, A1000} = 584 \times 10^{-5} \). Thus, the experimental sample was considered destroyed, if its deformations reached above the mentioned values [1]. The experimental values of the moment of crack formation and maximum permissible width of cracks opening are shown in table 4.

| The type of beams | The begin of crack formation | The maximum permissible cracks opening |
|------------------|-----------------------------|----------------------------------------|
|                  | M_{c}^{test}, [kN · m] | a_{c}^{d}, [mm] | M_{c}, [kN · m] | a_{c}^{d}, [mm] |
| B-1              | 1.01                       | 0.05          | 15.7           | 0.4             |
| B-2              | 1.06                       | 0.05          | 17.1           | 0.4             |
| B-3              | 0.96                       | 0.05          | 13.3           | 0.4             |

The cracks formation and the cracks opening caused the sharp growth of deformations in cross-sections of the experimental sample and, of course, the increase of deflections. Therefore, the value of the bending moment, which corresponded to an inflection on the chart of deflection, took for the moment of crack formation.

Further increase of loading was causing the growth of stresses in the compressive zone, the increase of the width of the crack opening, and the height of cracks. Accordingly, the experimental sample ceased to resist active forces and the stage of destruction was begun.

The beginning of the yielding flow in reinforcement A400C was happening earlier and under lesser values relative deformations than in reinforcement A1000. After the start of the yielding flow in reinforcement A400C, we observed a considerable increase of deformations’ growth in high-strength reinforcement and, of course, the growth of deflections in beams during further load for samples and
under fixed tensile load in reinforcement $f_{yk, A400C}$. All next increments of load were perceived high-strength reinforcement until its conventional yield strength was not reached. Even after the beginning of the yielding flow in reinforcement A400C, it continued to perceive part of the load, which was corresponded to its yield stress.

During the calculation of strength for the normal cross-section were determined such the stages of the work for reinforced masonry beams with combined reinforcement:

a) when the stress in reinforcement A400 C of reinforced masonry beams with combined reinforcement reached the yield point stress, there are observed the increase of the deformation growth and the deflection growth but the beams continued to perceive the growing loading;

b) during the beginning of the yielding flow in high-strength reinforcement A1000, the beam does not perceive the additional load, further loading of samples caused considerable deformations in reinforcement with the sharp excessive opening of cracks and certainly the growth of deflections;

c) physical destruction of beams, in particular the destruction of the compressive zone of beams.

During experimental studies, we carried out the analysis of the combined action of reinforcement and masonry with the formation of stress diagrams. The graphical correlations permitted to foresee the behavior of experimental samples under the next load and to determine the beginning of yielding flow in the reinforcement bar. The stress diagrams in reinforcement bars depending on the loading of the beam are shown in fig. 5.

The beams were designed in that way that the yielding flow of all tensile reinforcement bars of combined reinforcement began earlier than the destruction of the compressive zone of masonry. The destruction of experimental samples was plastic nature. Besides that, when the stress in reinforcement A1000 reached the yield point stress, the next loading caused the crush of the compressive zone of masonry. During the achievement of the yielding flow in reinforcement A400C the stress did not fall down in this reinforcement, in other words the reinforcement continued to perceive the corresponding maximum load and after its yielding flow.

The bending moment that corresponded to the yield point stress in reinforcement A400C was $M_1$, the value of maximum load, which was perceived by beam (under this load was happening the destruction of the compressive zone of the beam) was called – «limit (maximum) moment» - $M_{max}$.

The experimental and theoretical values of bearing capacity for beams and test loads of its physical destruction are presented in table 5.

We determined the change moment of the work for reinforced masonry beams with combined reinforcement from one stage to another by the stress diagrams in working reinforcement, taking into consideration the diagrams of experimental tests for the reinforcement and its deformations. During the test we carried out the analysis of the work of reinforcement and masonry using the stress diagrams. It was permitted to foresee the behavior of experimental samples under next loads, and also to determine the moment for the beginning of the yielding flow in reinforcement.

The determination of calculated values of bearing capacity of test reinforced masonry beams were carried out by the formulas [11]. The experimental and calculated values of limit (maximum) moments are shown in table 5.

The compressive strength of masonry for beams B-1 and B-2 was 9.06 MPa, and for beam B-3 – 7.15 MPa. The reinforcement percentage for beams B-1 and B-2 was 0.471 % and for beam B-3 – 0.956 %.

The destruction of beam B-1 was happened under the maximum bending moment that was equal to $21.9 \, \text{kN} \cdot \text{m}$. The theoretical maximum bending moment for this beam was $20.71 \, \text{kN} \cdot \text{m}$.

The beam B-2 was destroyed from bending moment, which was equal to $24.7 \, \text{kN} \cdot \text{m}$. The theoretical maximum bending moment for this beam was $23.61 \, \text{kN} \cdot \text{m}$.

The destruction of beam B-1 was happened under the maximum bending moment that was equal to $18.7 \, \text{kN} \cdot \text{m}$. The theoretical maximum bending moment for this beam was $17.06 \, \text{kN} \cdot \text{m}$. 
Figure 5. The stress diagrams in tensile reinforcement for beams B-1, B-2 and B-3

Table 5. The experimental and the theoretical values of bearing capacity of test beams and experimental loading of its physical destruction

| The type of beams | Experimental moment $M_1$ during the beginning of the yielding flow of the reinforcement A400C, [kN · m] | Experimental moment $M_{max}$ during under the physical destruction, [kN · m] | Theoretical moment by [10] $M_{sc}$, [kN · m] | $(M_{max}-M_N)/M_{max}$, % |
|------------------|------------------------------------------------|------------------------------------------------|---------------------------------|---------------------------------|
| B-1              | 18.6                                          | 21.9                                          | 20.71                           | 5.4                             |
| B-2              | 15.2                                          | 24.7                                          | 23.61                           | 4.6                             |
| B-3              | -                                             | 18.7                                          | 17.06                           | 8.8                             |
Conclusions

By theoretical and experimental studies were determined that the reinforced masonry beams with combined reinforcement by high-strength and normal steel continued to perceive the loading until the stress in the reinforcement A1000 do not reach the conventional yield strength.

Besides that, the physical destruction of the beam was happened after the beginning of the yielding flow of high-strength reinforcement A1000 and under the condition of sufficient reinforcement in the zone of action of maximum shears, in other words by total exhaustion of the summary bearing capacity of the reinforcements A400C and A1000.

The obtained experimental studies of bearing capacity for the reinforced masonry beams with combined reinforcement proved that the theoretical calculation of these beams by [10] is satisfactorily consistent with the bearing capacity of these structures (the difference is till 8.8%).

The crack formation in reinforced masonry beams with combined reinforcement generally occurred in the joints between the bricks.

References

[1] Kramarchuk A P, Ilnytskyy B M, Bobalo T V and Lytvyniak O Ya 2020 Bearing capacity of reinforced masonry beams with combined reinforcement Actual problems of Engineering mechanics: proceedings of VII International conference (Odessa) pp 182–186

[2] Ilnes Fayala, Oualid Limam and Ioannis Stefanou 2016 Experimental and numerical analysis of reinforced stone block masonry beams using GFRP reinforcement Composite Structures. Volume 152 pp 994-1006

[3] Illaria Cancelliere, Maura Imbimbo and Elio Sacco 2010 Experimental tests and numerical modeling of reinforced masonry arches Engineering Structures. Volume 32: Issue 3 pp 776–792

[4] Julia Nowak and Edyta Plebankiewicz 2018 Multicriteria assessment of selected types of ceilings MATEC Web of Conf. 219 04011

[5] Storozhenko L I and Zaslavets O O 2017 Experimental research of stone constructions firmness reinforced with steel profiles Collection of scientific works (branch machinery construction, building). (Yurij Kondratiuk Poltava State Technical University) Issue 8 pp 38-41

[6] Babych V E and Karavan M S 2010 Projecting of stone and stone reinforced constructions (Rivne)

[7] Rotko S V, Uzhgova O A and Zadorozhnikova І V 2010 Calculation of stone and reinforced stone constructions (Lutsk) p 355

[8] Vakhnenko P F 1990 Stone and reinforced stone constructions (Kyiv) p 184

[9] Pershakov V 2009 Reinforced Concrete and Stone Structures (Kyiv) p 304

[10] DSTU B V.2.7-23-95 Building mortars. General technical conditions (Kyiv: Min. bud-va, arkhit. ta zhytlovo-kom. hosp) p 40

[11] DBN V.2.6-162:2010 Stone and reinforced stone constructions. Design rules (Kyiv: Min. bud-va, arkhit. ta zhytlovo-kom. hosp) p 100

[12] DSTU V.2.6-156:2010 Structures of buildings and edifices. Concrete and reinforced concrete structures (Kyiv: Min. bud-va, arkhit. ta zhytlovo-kom. hosp) p 123

[13] DSTU B EN 1052-1:2011 Testing methods of stone masonry. Part 1. Finding out the firmness by compression. Design rules (Kyiv: Min. bud-va, arkhit. ta zhytlovo-kom. hosp) p 19