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Compressed-bent masonry walls reinforced with composite materials

Сжато-изгибаемые каменные стены, армированные композитными материалами

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Ключевые слова: каменные стены; сжато-изогнутые элементы; композитное армирование; несущая способность; кривые интеракции

Abstract. Despite the wide spread of surface composite reinforcement of masonry structures, there is not enough information concerning methods of calculating such reinforced structures in the actual normative literature. The article proposes a numerical model for estimating the effect of composite reinforcement on the bearing capacity of a compressed-bent masonry wall which is constructed on the basis of experimental studies of walls from cellular concrete blocks. The numerical model takes into account the plastic work of the masonry under compression and the possibility of crack formation. Theoretical curves are obtained for the dependence of the bearing capacity of reinforced and non-reinforced masonry on the relationship between the compressive force and the bending moment. It is shown that the accepted reinforcement gives the greatest effect in the range of loads from pure bending to compression with bending at a compressive load value equal to half the failure load under pure compression. Such numerical design model can be used to evaluate the effect of reinforcing vaults and walls loaded eccentrically, or from the plane, and other similar structures.

Аннотация. Несмотря на широкое распространение поверхностного композитного армирования каменных конструкций, в современной нормативной литературе не хватает информации, касающейся методов расчёта таких армированных конструкций. В статье предложена численная модель оценки влияния композитного армирования на несущую способность сжато-изгибаемой каменной стены, построенная на основе экспериментальных исследований стен из ячеистобетонных блоков. Численная модель учитывает пластическую работу кладки при сжатии и возможность образования трещин. Получены теоретические кривые зависимости несущей способности армированной и не армированной кладки от соотношения между сжимающей силой и изгибающим моментом. Показано, что принятое армирование даёт наибольший эффект в диапазоне нагружений от чистого изгиба до сжатия с изгибом при величине сжимающей нагрузки в половину от разрушающей при чистом сжатии. Подобная численная модель конструкции может быть использована для оценки эффекта армирования сводов, стен, нагруженных внецентренно, либо из плоскости, и других подобных конструкций.

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1. Introduction

Except vertical load masonry walls can be exposed to horizontal actions that can be caused for example from wind, lateral pressure of the ground on the walls of basements, etc. In this case, the wall should be calculated as compressed-bent element. Compression with a bend can also occur in walls at their eccentric loading by overlapping.

The methodology for calculating these walls is described in the technical and normative literature [1]. Bearing capacity of walls limits by resistance of the masonry in the compressed zone of the cross sections or by the loss of their stability under certain combinations of compression and bending. In some cases, the bending moments that cause tension of the masonry parallel to horizontal mortar joints can be defining value (Figure 1).

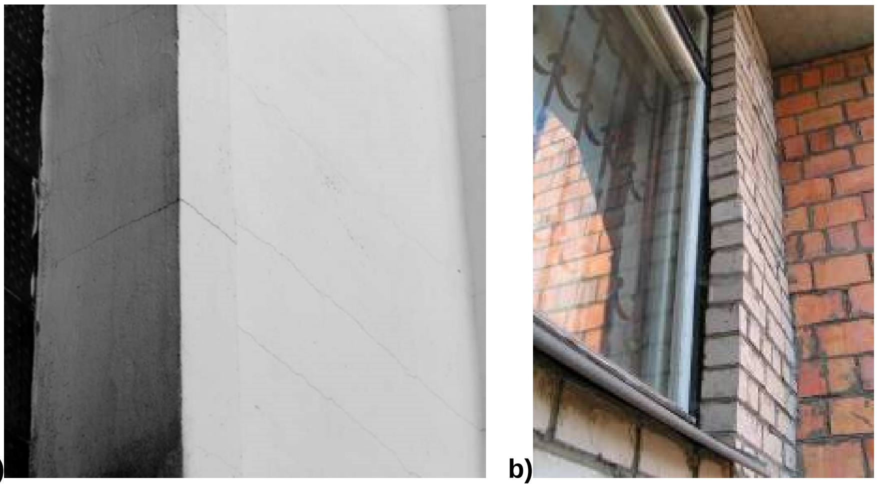

a) b)

Figure 1 - Typical damages of eccentric-compressed masonry walls:
a) horizontal cracks on the tensile surface of the partition wall;
b) loss of stability of the facing layer of masonry

In general, bearing capacity of masonry walls subjected both vertical and horizontal loads depends on their flexibility, the values of the eccentricities of the place of applying of the vertical load, flexural stiffness of the masonry and its mechanical parameters and resistance to vertical and horizontal loads, i.e. from their interaction. It should be noted that the walls with their eccentric loading are most often studied in the scientific and technical literature [2–10]. The study of walls on the simultaneous action of horizontal and vertical loads is very rare. This is associated with the difficulties of experiment conducting. The increased sensitivity to cracking is one of their defects, especially in action of horizontal loads. In this regard, according to [1], the design of masonry structures elements that works on bending parallel to horizontal mortar joints is not allowed.

The problem can be solved by surface reinforcement of walls with a meshes from composite materials.

According to this technology, the moistened masonry surface should be covering with a thin layer of a mortar of inorganic mineral materials with modified polymeric additives, into which a reinforcement mesh from composite materials is embedded. Then protection plaster layer should be applying with thickness of 8–10 mm, and then its surface is subjected to finishing treatment. If it's necessary, the second reinforcement mesh can be deposited in the protective layer that will be providing increased strength of strengthening zone [11]. This system is known abroad as FRCM (Fiber Reinforced Cementitious Matrix) and one of its varieties is the system Ruredilx Mesh. A carbon fiber reinforcement meshes can be used in this strengthening system with the following mechanical properties: tensile strength – *4800 MPa*; modulus of elasticity – *240 GPa*; tensile break strain – *1.8 %.* Aramid and glass fiber reinforcement meshes are also used. Recently, basalt fibers reinforcement meshes have been used in Russia [12].

The way that is considered has the following advantages:

– simple technology;

– high adhesion of reinforcement plaster layer to the surface of masonry;

– high compatibility of reinforcement layer with masonry; i.e. approximate deformation characteristics, such as modulus of elasticity, thermal expansion coefficients;

– high fire resistance, corrosion resistance, water resistance and vapor permeability, which makes it possible to reinforce masonry structures both inside and outside buildings.

The advantages of this method of are its universality and the possibility of using it for all shapes of structures.

Composite reinforcement is used not only for surface reinforcement, but also in some cases inside the masonry joints to increase the shear resistance [13].

For brick walls, studies were carried out on the out-of-plane load with reinforcement by this technology. [14–20]. These studies showed a significant dependence of the form of failure on the properties of the solution used. It was also shown that additional strengthening of the compressed side of the masonry does not affect its strength.

The strengthening improvement in the behavior of the masonry in the zone of plastic deformations was also shown in [21] using a similar technology with a GFRP mesh.

An alternative to reinforcing composite materials is the traditional surface reinforcement with a steel mesh [22]. This solution can also be effective, but it has very limited field of utilization.

To analyze the strengthening of the masonry by surface reinforcement, known finite-element models are used [23–28], which take into account plastic deformations and the possibility of initiation and development of cracks. In this study, the simulation is performed to obtain interaction curves of the ultimate bending moment and the compressive force.

It should be noted that, in spite of the available practical experience and wide variety of experimental and theoretical studies, very limited data on methods of calculating masonry structures that are reinforced with composite materials are contained in the foreign, as well as in the domestic normative literature. In many cases, reinforcement is assigned by the so-called "engineering intuition" method without proper calculation justification.

In this paper, the results of experimental and theoretical studies of walls of cellular concrete blocks, which have recently become increasingly practical, have been presented. The main task of the research was to build a numerical model on the basis of experimental data to assess the effect of composite reinforcement on the load-carrying capacity of a compressed-bent masonry wall, depending on the ratio of the compressive force and the bending moment.

2. Methods

A known simulation models of reinforced masonry structures constructed by analogy with reinforced concrete structures (based on static balance of external and internal loads in the calculated cross sections) make it possible to obtain a relatively good convergence with experiments only for the simplest cases, for example, of bent elements [29]. In this regard, the experimental studies of reinforced and unreinforced masonry specimens from cellular concrete blocks, which were tested for compression with bending according to the scheme shown in Figure 2, have been carried out by the authors. Specimens were made from blocks with dimensions *12 x 50 x 24 cm* and a density $\gamma = 700$ kg/m^3, connected together on thin glue mortar joints. Compressive strength of cellular concrete blocks was $R_c = 3.24$ *MPa*, and tensile strength $R_t = 0.39$ *MPa* according to laboratory tests.

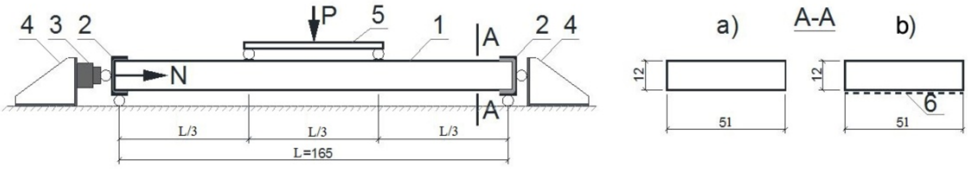


Figure 2. Scheme of tests of unreinforced (a) and reinforced (b) masonry compression specimens with bending (dimensions in cm)
1 – test specimen, 2 – steel frame, 3 – hydraulic jack that creates a compressive force *N*,
4 – steel seats, 5 – distributing beam for force transfer *P*,
6 – mesh reinforcement from composite materials

As a reinforcement we used fiberglass meshes of the trade mark Mapegrid G220 of the Italian company Mapei. The tensile strength of the grids that was declared by the company is *45 kN* per *1 m* of width, and the tensile break strain of *3 %*.

We tested one specimen with reinforcement and without reinforcement (specimens No. 1) in order to determine the load-carrying capacity M_{RD} at bending. The same number of specimens was tested to determine their load-bearing capacity N_{RD} in compression (specimens No. 5). The rest of the specimens (3 – without reinforcement and 3 – with reinforcement) were tested under the combined action of the longitudinal force and the bending moment $M = PL/6$ caused by the action of the force P. At the same time during loading, the force N was maintained at the same level, and the force P increased until the specimens were destroyed.

The calculations were carried out using the ABAQUS software in a non-linear setting. An iterative procedure was used, according to which the values of the modulus of elasticity of the material of the cellular concrete blocks were refined for each loading level. The plastic behavior of the masonry was also taken into account, which was specified for cases of exceeding the modulus of elasticity limit. A model of the so-called expanded finite element method was also used, which took into account the possibility of crack formation in the masonry and their effect on the stress-strain state of the structure. The design scheme was adopted similar to that depicted in Figure 2, in a plane stress condition using rectangular finite elements. The contact of the steel frame with the masonry specimen was simulated by a free contact "surface to surface" [30] without a rigid interface of the contact zone. The contact of the reinforcement and masonry was taken rigid. In this case, modulus of elasticity were set for reinforcement, taking into account the possibility of its work only in one direction – tension. This was necessary to exclude the possibility of incorporating reinforcement into compression work. When calculating an appropriate limiting moment was selected by iteration with an increment of *0.05 kNm* for each level of the compressive force, with a step of *10–20 kN*.

3. Results and Discussion

The main results of testing the experimental specimens are presented in Table 1, from which it follows that the load-bearing capacity of the specimens increases with increasing axial compressive force to the level $N = (0.4 \dots 0.5)N_{RD}$, and the load-bearing capacity decreases at a higher level N. At the same time, the reinforced specimens showed a higher load-bearing capacity with bending compression in comparison with unreinforced specimens.

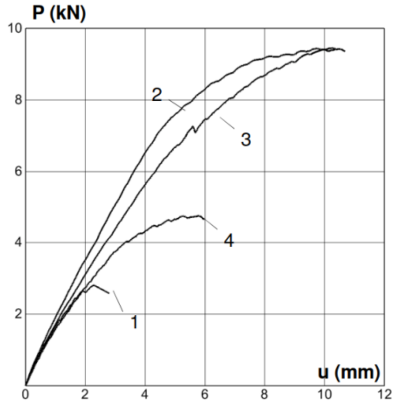
Table 1. The values of the limiting bending moments $M = PL/6$ as a function of the compressive force N

No. of specimen		1	2	3	4	5
Specimens without reinforcement	M (kN·m)	0.39	1.18	1.95	0.98	0
	N (kN)	0.0	40.0	80.0	120.0	165.4
Reinforced specimens	M (kN·m)	0.77	2.60	2.59	1.30	0
	N (kN)	0.0	40.0	80.0	120.0	178.9

As an example, the type of unreinforced specimen No. 3 before and after failure from the combined action of longitudinal force and bending moment have been showed on the Figure 3. The failure was fragile and occurred as a result of crushing the aerated concrete in a compressed zone.

Figure 3. Type of test specimens during loading and after failure

Figure 4 shows the experimental dependences of the maximum deflections reinforced specimens *u* on the load *P*. At the level of the compressive force $N=(0...0.25)\cdot N_{RD}$, the failure of the specimens occurred as a result of tension breaking of the reinforcement meshes, and at higher levels – as a result of the exhaustion strength of cellular concrete on the compression. It also follows from the dependences that the compression of specimens by a force $N=(0.25...0.5)\cdot N_{RD}$ leads to a substantial increase of the failure load *P*.



1 – $N=0$; 2 – $N=0.25\cdot N_{RD}$; 3 – $N=0.50\cdot N_{RD}$; 4 – $N=0.75\cdot N_{RD}$

Figure 4. Experimental dependences of the maximum deflections *u* of reinforced specimens on the load *P* at a constant value of the compressive force *N*

Figure 5 shows the interaction curves “M_{Rd}–N_{Rd}“that were obtained by calculation. Experimental values of the load-bearing capacity of the specimens less than the calculated values by *10…25 %*. This discrepancy can be explained by the fact that the calculations did not take into account such factors as a variation of the geometric dimensions of the specimens, the effect of deflections on the change in the design scheme, and the idealized form of the applied loads.

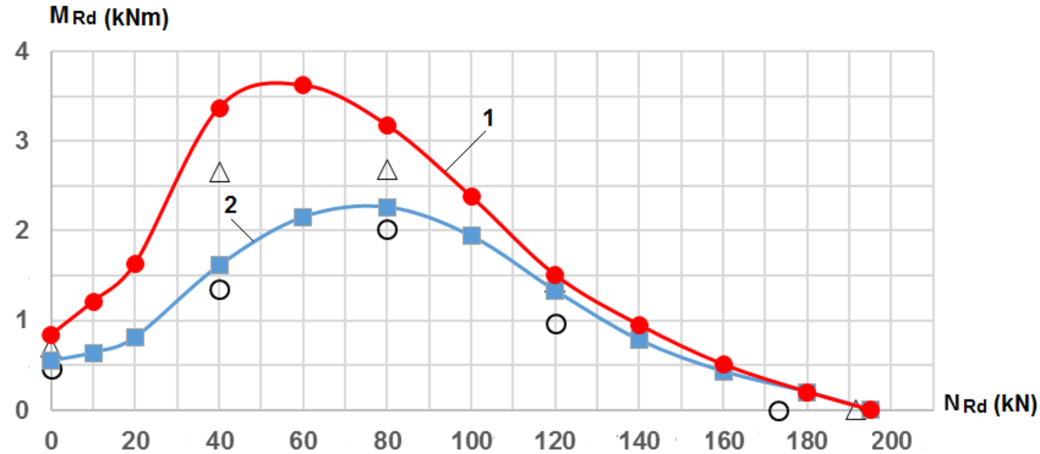


Figure 5. Interaction curves “M_{Rd}–N_{Rd}”
1 – for reinforced specimens; 2 – for unreinforced specimens;
∆ – experimental values for reinforced specimens; ○ – experimental values for unreinforced specimens

An example of the stress-strain state of a reinforced specimen that corresponds to the forces *N = 120 kN* and *M = 1.51 kN·m* is shown in the Figure 6. In this case, we see an nonuniform distribution of stresses caused by the appearance of lustic deformations in the compressed zone, corresponding to the crushing of the masonry area and the subsequent occurrence of tensile stresses on the lower surface of the specimen.

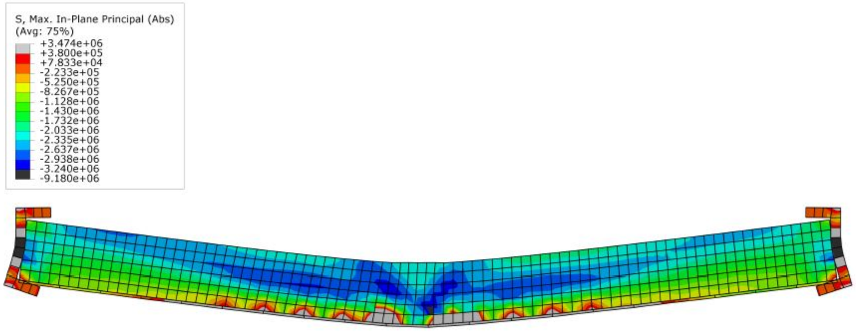


Figure 6. Stress-strain state of a reinforced specimen under action *N=120 kN и M=1.51 kN·m*

It is characteristic, that for load level $N=(0.0…0.5)\cdot N_{RD}$, the bending load capacity increased more than *2* times, while at a higher level of force *N* this increase did not exceed *30 %*. In specimens that work only in bending, the availability of reinforcement has increased the bearing capacity of the M_{RD} almost by 100 %, while specimens that work only in compression – only by 8 %. The reinforcement effects for different loading levels correlate with mechanical fracture of the specimens. At low levels of force *N*, the failure occurred as a result of tension breaking of the reinforcement meshes, and at higher levels – as a result of crushing the masonry in the compressed zone. The results of an experimental study of masonry specimens with eccentric loading, carried out by I. Talero and I. Delgado [31].

Despite some excess the data of the numerical simulation are in qualitative agreement with the experimentally obtained values. Sections of the interaction curves for stress states that are close to pure compression ($0.75...1\cdot N_{RD}$) have relationships between the maximum loads for reinforced and unreinforced specimens, which differ slightly from the experimental data, up to the coincidence of theoretical curves at $0.9...1\cdot N_{RD}$. Presumably this is caused by the possibility of cracks formation in the direction along the compressive force that has not been considered in the numerical model. The interaction curves that were obtained from the results of numerical simulation are in good agreement with the data of the studies T. Hrynyk and J. Myers [32].

4. Conclusion

The results of experimental study showed that strengthening the compressed-bent masonry from cellular concrete blocks with glass fiber reinforcement meshes causes a significant increase in its bearing capacity. The greatest effect with strengthening is achieved in the action of a compressive load, equal to *0.25...0.5* from the failure load.

A nonlinear finite element model that was calibrated on the basis of experimental data was developed. The model that was presented gives the possibility for a better qualitative understanding of the failure mechanism of the reinforced specimen for various combinations of longitudinal and lateral loads. The transition from failure due to the formation of cracks in the tensile zone to failure from loss of stability due to nonuniform plastic deformations of the masonry in the compressed zone is very evident.

The numerical results that were obtained are in good agreement with both the experimental data and with similar studies of compressed-bent masonry elements that were performed by other authors. Such numerical simulation models can be used in assessing the behavior of various compressed-bent masonry structures, such as vaults loaded eccentrically or from the plane of the wall and other similar structures. At the same time, this numerical model does not take into account the possibility of crack formation in the direction of the compressive force, which causes insufficient accuracy of the results for stress states close to pure compression. It is recommended to apply classical methods of strength evaluation for such states.

Experimental and theoretical study of reinforced vault structures and vertical masonry walls when they loaded from the plane is assumed as a further development of the study.

References

1. *Russian Construction Set of Rules SP 15.13330.2012* Kamennyye i armokamennyye konstruktsii [Masonry and reinforced masonry structures]. Moscow, 2012. 81 p. (rus)
2. Orlovich R.B., Chakalidi V.Kh., Bespalov V.V. Strenthening of masonry elements with composite mesh under compression and compression combined with bending. *Construction and reconstruction.* 2017. No. 5(73).

Литература

1. СП 15.13330.2012 Каменные и армокаменные конструкции. Москва, 2012. 81 с.
2. Орлович Р.Б., Чакалиди В.Х., Беспалов В.В. Усиление сжатых и сжато-изгибаемых каменных элементов сетками из композитных материалов // Строительство и реконструкция. 2017. № 5(73). С. 45–49.
3. Martin A., Esnault J.-B., Massin P. About the use of

Pp. 45–49. (rus)

3. Martin A., Esnault J.-B., Massin P. About the use of standard integration schemes for X-FEM in solid mechanics plasticity. *Computer Methods in Applied Mechanics and Engineering.* 2015. No. 283. Pp. 551–572.
4. Orlovich R.B., Chakalidi V.Kh. Strengthening methods for cylindrical masonry vaults. *Construction and reconstruction.* 2017. No. 1(69). Pp. 51–54. (rus)
5. Orłowicz R., Jaworski R., Drobiec Ł. Influence of reinforcement on the load-bearing capacity of cellular concrete walls subjected to compression with bending. *Building Inspection.* 2015. No. 10. Pp. 31–33.
6. McGinley W.M., Corzo A.M., Gergely J., Foster P.B., Young D.T. A design methodology for FRP systems for masonry structures. *10th Canadian Masonry Symposium, Banff, Alberta.* 2005. Pp. 34–44.
7. Garmendia L., San-Mateos R., García D., Gandini A., San-José J.T., Marcos I. Retrofitting of masonry vaults with composite materials. *Structural Analysis of Historical Constructions.* Leuven, Belgium. 2016. Pp. 351–356.
8. Hamed E., Rabinovitch O. Failure characteristics of FRP-strengthened masonry walls under out-of-plane loads. *Engineering Structures.* 2010. No. 32. Pp. 2134–2145.
9. Anania L., Agata G., Giaquinta C., Badala A. Out of Plane Behavior of Calcareous Masonry Panels Strengthened by CFRP. *APCBEE Procedia.* 2014. No. 9. Pp. 401–406.
10. Furtado A., Rodrigues H., Arede A., Varum H. Experimental Characterization of the In-plane and Out-of-Plane Behaviour of Infill Masonry Walls. *Procedia Engineering.* 2015. No. 114. Pp. 862–869.
11. Orlovich R.B., Derkach V.N. Zarubezhnyy opyt armirovaniya kamennykh konstruktsiy [Foreign experience of reinforcement of masonry structures]. *Zhilishchnoye stroitel'stvo.* 2011. No. 11. Pp. 35–39. (rus)
12. *Al'bom tekhnicheskikh resheniy po primeneniyu bazal'tovoy setki GRIDEKS v stroitel'stve* [Album of technical solutions for the application of the GRIDEX basalt grid in construction]. Moscow, 2016. (rus)
13. Miccoli L., Mueller U., Fontana P. In-plane shear behaviour of earthen materials panels strengthened with polyester fabric strips. *10th International Conference on Structural Analysis of Historical Constructions.* Leuven, Belgium. 2016. Pp. 1099–1105.
14. Bernat-Maso E., Escrig C., Aranha C. A. Gil L. Experimental assessment of Textile Reinforced Sprayed Mortar strengthening system for brickwork wallettes. *Construction and Building Materials.* 2014. No. 50. Pp. 226–236.
15. Gattesco N., Boem I. Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study. *Composites Part B: Engineering*. 2017. No. 128. Pp. 39–52.
16. Anil O., Tatayoğlu M., Demirhan M. Out-of-plane behavior of unreinforced masonry brick walls strengthened with CFRP strips. *Construction and Building Materials.* 2012. No. 35. Pp. 614–624.
17. Dizhur D., Griffith M., Ingham J. Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips. *Engineering Structures.* 2014. No. 59. Pp. 330–343.
18. Kadam S., Singh Y., Li B. Out-of-plane behaviour of unreinforced masonry strengthened using ferrocement overlay. *Materials and Structures.* 2014. No. 48(10). Pp. 3187–3203.
19. Bengi A., Emre E., Ali D. Strengthening of brick masonry with PVA fiber reinforced cement stucco. *Construction and Building Materials.* 2015. No. 79. Pp. 255–262.
20. Sachin B.K., Yogendra S., Bing L. Strengthening of unreinforced masonry using welded wire mesh and micro-

standard integration schemes for X-FEM in solid mechanics plasticity // Computer Methods in Applied Mechanics and Engineering. 2015. № 283. Pp. 551–572.

4. Орлович Р.Б., Чакалиди В.Х. Способы усиления цилиндрических каменных сводов // Строительство и реконструкция. 2017. № 1(69). С. 51–54.
5. Orłowicz R., Jaworski R., Drobiec Ł. Influence of reinforcement on the load-bearing capacity of cellular concrete walls subjected to compression with bending // Building inspection. 2015. № 10. Pp. 31–33.
6. McGinley W.M., Corzo A.M., Gergely J., Foster P.B., Young D.T. A design methodology for FRP systems for masonry structures // 10th Canadian Masonry Symposium, Banff, Alberta. 2005. Pp. 34–44.
7. Garmendia L., San-Mateos R., García D., Gandini A., San-José J.T., Marcos I. Retrofitting of masonry vaults with composite materials // Structural Analysis of Historical Constructions, Leuven, Belgium. 2016. Pp. 351–356.
8. Hamed E., Rabinovitch O. Failure characteristics of FRP-strengthened masonry walls under out-of-plane loads // Engineering Structures. 2010. № 32. Pp. 2134–2145.
9. Anania L., Agata G., Giaquinta C., Badala A. Out of Plane Behavior of Calcareous Masonry Panels Strengthened by CFRP // APCBEE Procedia. 2014. № 9. Pp. 401–406.
10. Furtado A., Rodrigues H., Arede A., Varum H. Experimental Characterization of the In-plane and Out-of-Plane Behaviour of Infill Masonry Walls // Procedia Engineering. 2015. № 114. Pp. 862–869.
11. Орлович Р.Б., Деркач В.Н. Зарубежный опыт армирования каменных конструкций // Жилищное строительство. 2011. № 11. С. 35–39.
12. Альбом технических решений по применению базальтовой сетки ГРИДЕКС в строительстве. Москва, 2016.
13. Miccoli L., Mueller U., Fontana P. In-plane shear behaviour of earthen materials panels strengthened with polyester fabric strips // 10th International Conference on Structural Analysis of Historical Constructions. Leuven, Belgium. 2016. Pp. 1099–1105.
14. Bernat-Maso E., Escrig C., Aranha C. A. Gil L. Experimental assessment of Textile Reinforced Sprayed Mortar strengthening system for brickwork wallettes // Construction and Building Materials. 2014. № 50. Pp. 226–236.
15. Gattesco N., Boem I. Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study // Composites Part B: Engineering. 2017. № 128. Pp. 39-52.
16. Anil O., Tatayoğlu M., Demirhan M. Out-of-plane behavior of unreinforced masonry brick walls strengthened with CFRP strips // Construction and Building Materials. 2012. № 35. Pp. 614–624.
17. Dizhur D., Griffith M., Ingham J. Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips // Engineering Structures. 2014. № 59. Pp. 330–343.
18. Kadam S., Singh Y., Li B. Out-of-plane behaviour of unreinforced masonry strengthened using ferrocement overlay // Materials and Structures. 2014. № 48(10). Pp. 3187–3203.
19. Bengi A., Emre E., Ali D. Strengthening of brick masonry with PVA fiber reinforced cement stucco // Construction and Building Materials. 2015. № 79. Pp. 255–262.
20. Sachin B.K., Yogendra S., Bing L. Strengthening of unreinforced masonry using welded wire mesh and micro-concrete. Behaviour under in-plane action // Construction and Building Materials. 2014. № 54. Pp. 247–257.
21. Gattesco N., Gubana A., Melotto M. GFRP to strengthen masonry walls: Numerical analysis and evaluation of the different mechanical parameters role // 10th International

concrete. Behaviour under in-plane action. *Construction and Building Materials.* 2014. No. 54. Pp. 247–257.

21. Gattesco N., Gubana A., Melotto M. GFRP to strengthen masonry walls: Numerical analysis and evaluation of the different mechanical parameters role. *10th International Conference on Structural Analysis of Historical Constructions.* Leuven, Belgium. 2016. Pp. 357–364.
22. Shermi C., Dubey R.N. Study on out-of-plane behaviour of unreinforced masonry strengthened with welded wire mesh and mortar. *Construction and Building Materials.* 2017. No. 143. Pp. 104–120.
23. Pourfalah S., Suryanto B., Cotsovos D.M. Enhancing the out-of-plane performance of masonry walls using engineered cementitious composite. *Composites Part B: Engineering.* 2018. No. 140. Pp. 108–122.
24. Bellini A., Mazzotti C. Bond behavior and tensile properties of FRCM composites applied on masonry panels. *Composite Structures.* 2016. No. 143. Pp. 322–329.
25. Reboul N., Si Larbi A., Ferrier E. Two-way bending behaviour of hollow concrete block masonry walls reinforced by composite materials. *Composites Part B: Engineering.* 2018. No. 137. Pp. 163–177.
26. Natalino G., Ingrid B. Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study. *Composites Part B: Engineering.* 2017. No. 128. Pp. 39–52.
27. Sarkar N.-E.-K., Manicka D., David P.T. Out-of-plane deformation and failure of masonry walls with various forms of reinforcement. *Composite Structures.* 2016. No. 140. Pp. 262–277.
28. Alessia M., Giovanni M., Calogero C., D'Anna J., La Mendola L. Finite element analysis of the out-of-plane behavior of FRP strengthened masonry panels. *Composites Part B: Engineering.* 2017. No. 115. Pp. 188–202.
29. Papanikolau C., Triantafillou T., Fabregat P.R. Increase of load-carrying capacity of masonry with textile reinforced rendering. *Mauerwerk.* 2015. No. 19. Pp. 40–51.
30. *Abaqus documentation user manual, v. 6.14.* Dassault Systems, 2014.
31. Valetta G., Pedemonte G., Fontana J.J., Talero R., Delgado A. Fibreglass Reinforcement in Brick Bearing Walls. *7th international masonry conference.* London, UK. 2006. Pp. 142–149.
32. Hrynyk T., Myers J. J. Comparative study on the out-of-plane behavior of retrofitted masonry wall systems with arching action. *10th North American Masonry Conference.* 2007. Pp. 305–316.

Conference on Structural Analysis of Historical Constructions. Leuven, Belgium. 2016. Pp. 357–364.

22. Shermi C., Dubey R.N. Study on out-of-plane behaviour of unreinforced masonry strengthened with welded wire mesh and mortar // Construction and Building Materials. 2017. № 143. Pp. 104–120.
23. Pourfalah S., Suryanto B., Cotsovos D.M. Enhancing the out-of-plane performance of masonry walls using engineered cementitious composite // Composites Part B: Engineering. 2018. № 140. Pp. 108–122.
24. Bellini A., Mazzotti C. Bond behavior and tensile properties of FRCM composites applied on masonry panels // Composite Structures. 2016. № 143. Pp. 322–329.
25. Reboul N., Si Larbi A., Ferrier E. Two-way bending behaviour of hollow concrete block masonry walls reinforced by composite materials // Composites Part B: Engineering. 2018. № 137. Pp. 163–177.
26. Natalino G., Ingrid B. Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study // Composites Part B: Engineering. 2017. № 128. Pp. 39–52.
27. Sarkar N.-E.-K., Manicka D., David P.T. Out-of-plane deformation and failure of masonry walls with various forms of reinforcement // Composite Structures. 2016. № 140. Pp. 262–277.
28. Alessia M., Giovanni M., Calogero C., D'Anna J., La Mendola L. Finite element analysis of the out-of-plane behavior of FRP strengthened masonry panels // Composites Part B: Engineering. 2017. № 115. Pp. 188–202.
29. Papanikolau C., Triantafillou T., Fabregat P.R. Increase of load-carrying capacity of masonry with textile reinforced rendering // Mauerwerk. 2015. № 19. Pp. 40–51.
30. Abaqus documentation user manual, v. 6.14, Dassault Systems, 2014.
31. Valetta G, Pedemonte G., Fontana J. J., Talero R., Delgado A. Fibreglass Reinforcement in Brick Bearing Walls // 7th international masonry conference. London, UK. 2006. Pp. 142–149.
32. Hrynyk T., Myers J. J. Comparative study on the out-of-plane behavior of retrofitted masonry wall systems with arching action // 10th North American Masonry Conference. 2007. Pp. 305–316.

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