WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2020.131794
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVI ISSUE 2 2020

EFFECTIVENESS OF SHEAR STRENGTHENING OF WALLS MADE USING AAC BLOCKS - LABORATORY TEST RESULTS

M. KAŁUŻA[1]

The selection of the most proper strengthening method/system with an assessment of its effectiveness is quite complicated in the case of masonry structures, mainly due to their huge diversity in materials. The most popular strengthening materials based on the composite fibres and are laid on the masonry wall using epoxy adhesives (FRP system) or mineral mortars (FRCM system). This article presents a comparison of external strengthening made using different glass-fibre-based materials on the behaviour of specific masonry walls. The walls are made of AAC blocks (Autoclaved Aerated Concrete), commonly used in rather low urban buildings or skeleton construction. As a strengthening material the GFRP sheets and two types of glass meshes are used. The walls are subjected to diagonal compression, which reflects the shearing of the walls. The scope of research describes cracking stage, shear capacity and analysis of the mode of failure of tested walls.

Keywords: masonry structures, strengthening, FRP/FRCM system, in-plane shearing, effectiveness, AAC blocks

1. Introduction

Masonry structures are very sensitive to in-plane actions, especially those that cause shearing of the walls. This is due to the specifics of masonry, which are composed of brittle or quasi-brittle materials with a very low cracking resistance. The external strengthening is the best method to prevent premature cracking of the walls with a simultaneous increase in shear capacity. However,

[1] PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland.

the selection of effective strengthening is very complicated due to the huge amount of masonry components and different erecting techniques. Every combination of masonry elements and specific type of mortar require an individual analysis in terms of effectiveness of the strengthening system adopted, which should base on the laboratory tests [1, 4, 6].

Nowadays, the most popular strengthening materials are fibre composites applied on the masonry surface using epoxy adhesives (typical FRP system) or mineral mortars (FRCM system). The advantages of FRP system used as strengthening of masonry are generally known [5, 7]; however, there are some disadvantages of this solution, which makes it not quite suitable in masonry applications. The main problems are very high strength with low flexibility of the adhesive used, which causes an undesirable failure of masonry substrate (delamination) and very low vapour permeability, which disturbs the free exchange of moisture that the masonry structure provides.

The FRCM system is a relatively new solution, much more compatible with the masonry substrate. It uses organic (mostly cementations-based) matrixes, instead of epoxy resins, which provide unchanged physical properties of the masonry wall. As a reinforcing of the external strengthening layer different composite meshes/grids are used. The influence of this system on the different masonry structures is still being tested and analysed [2, 3].

This paper presents a comparison of two strengthening systems (FRP and FRCM) applied on the masonry walls made of AAC blocks and subjected to in-plane shearing.

2. RESEARCH ASSUMPTIONS

2.1. MATERIALS

The walls are made of AAC blocks and built with thin bed joints and unfilled head joints. The blocks are characterized by very low compressive strength amounted to 4.65 N/mm^2. The mortar used is dedicated to the thin joints. Its compressive strength determined during laboratory tests amounted to 12.4 N/mm^2.

The strengthening of AAC walls was made using materials based on different glass fibres. The first strengthening system consisted of GFRP woven mesh (sheet) glued on the wall surface using epoxy resin. This is a typical FRP (Fibre Reinforced Polymer) system based on high-strength and weight-light fibres and epoxy adhesive. Subsequent strengthening was made using FRCM system. Two types of strengthening sets consisted of glass mesh and cement-based mortar (mineral adhesive) were used. The mesh type 1 was a typical C-glass mesh (alkali-resistant) with a mesh size of

4.0 × 4.5 mm used in a plastering system (Fig. 1a). The other mesh (type 2) was a systemic pre-primed alkali-resistant glass fiber mesh with a mesh size of 25 × 25 mm (Fig. 1b).

The properties of all strengthening materials and epoxy resin are taken from the technical papers of the manufactures. However, both mortars were laboratory tested according to the standard EN 1015-11. The first type of mortar was used in typical plastering systems. The second one is a systemic mortar dedicated to masonry strengthening. This mortar is reinforced by polymer fibers. The main properties of strengthening materials and adhesives are summarized in Table 1 and 2.

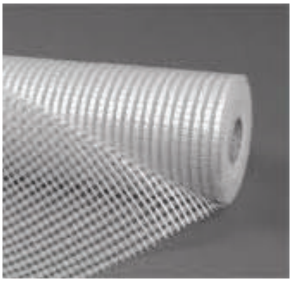
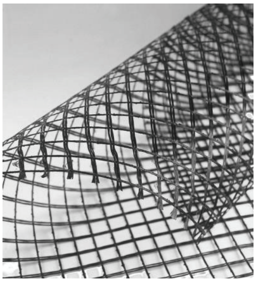
a)  b) 

Fig. 1. Strengthening glass-mesh: a) used in plastering works, b) systemic solution

Table 1. Properties of glass materials

Strengtening material	Density [g/m^2]	Failure force [N/mm]	Elongation at failure [%]
GFRP sheet	350	195	4.3
GFRP mesh - type 1	145	35	4.5
GFRP mesh - type 2	225	45	3.0

Table 2. Properties of used adhesives

Adhesive	Compressive strength [N/mm^2]	Flexural strength [N/mm^2]	Modulus of elasticity [N/mm^2]
Epoxy resin	≥ 1000	-	≥ 3200
Plastering mortar	12.8	4.2	4020
Systemic mortar	25.8	6.7	7320

2.2. TESTING SERIES

Fourteen masonry walls with the dimensions of 805×900×240 mm were tested and analysed. Five testing series were distinguished. The first one including unstrengthened walls (Y-US) served as a comparative series. Two further series consisted of walls strengthened in two configurations using FRP system (marked as I). The strengthening material – GFRP sheets – was arranged in strips with a width of 200 mm. In Y-GFRP-I.A series the strips covered the vertical, unfilled joins, while in Y-

GFRP-I.B series the strips were located between the vertical joins (Figs. 2a and 2b). The last two series included walls strengthened using FRCM system (marked as II), where the superficial strengthening was applied. The Y-GFRP.1-II series was made using the glass mesh type 1 and plastering mortar, while the Y-GFRP.2-II series covered a widely available strengthening system (i.e. glass mesh type 2 and systemic mortar with fibers). The list of all series is presented in Table 3. In all cases, the strengthening was made on both sides of the walls.

The elements were subjected to diagonal compression according to the standard RILEM LUMB 6.

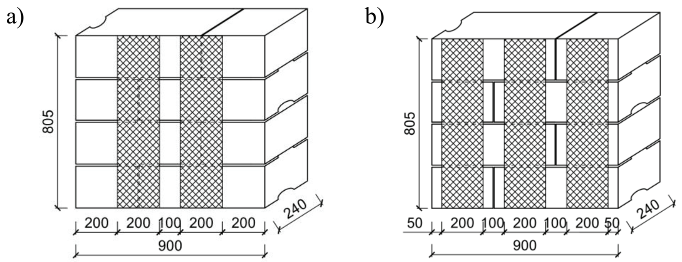


Fig. 2. Set of the GFRP sheets: a) arrangement A, b) arrangement B

Table 3. Characterization of tested series

Strengtening material	Number of tested models	Type of strengtnening	Type of materials used
Y-US-i	4	None	None
Y-GFRP-I.A-i	3	Strips in arragement A	Glass sheet
Y-GFRP-I.B-i	1	Strips in arragement B	Glass sheet
Y-GFRP.1-II-i	3	Superficial	Glass mesh - type 1
Y-GFRP.2-II-i	3	Superficial	Glass mesh - type 2

3. SHEAR STRESSES AND MODE OF FAILURE

3.1. UNSTRENGTHENED MODELS

In all unstrengthened walls no premature cracking preceding the failure of the element was observed. The cracking, reaching the maximum load and final failure appeared in the same moment. Thus, the first visible crack was tantamount to the total destruction of the element. The formation of crack always started at the unfilled joint, which consequently led to one diagonal crack running through the masonry element. In Fig. 3 a typical failure of unstrengthened wall is shown.

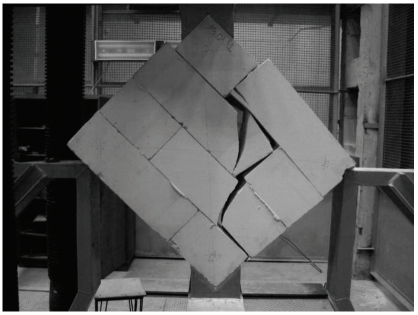


Fig. 3. The view of damaged model without strengthening

The mode of failure recognized in all unstrengthened walls was undesirable due to its fragile and sudden nature. The shear stresses calculated as a product of force measured and surface along the diagonal are identical in all characteristic moments. The values are summarized in Table 4.

Table 4. Main stresses recorded in unstrengthened models

Models	Cracking stress [N/mm^2]	Maximum stress [N/mm^2]	Failure stress [N/mm^2]
Y-US-1	0.380	0.380	0.380
Y-US-2	0.364	0.364	0.364
Y-US-3	0.344	0.344	0.344
Y-US-4	0.349	0.349	0.349
Mean value:	**0.359**	**0.359**	**0.359**

3.2. FRP SYSTEM

The most important observation of the behaviour of walls strengthened using GFRP strips was a significant influence of the strengthening arrangement. The positive impact of the strengthening was noticed only in the walls, in which the unfilled joints were covered by the composite strips – Y-GFRP-I.A. The application of GFRP sheets in the arrangement B (see Fig. 2b) caused very fast and extensive failure of the element. In both series the visible cracking of the wall appeared before final failure, but in element Y-GFRP-I.B-1 it happened very early; at the stress of 0.235 N/mm^2. The cracking of walls strengthened in arrangement A was observed much later (at much higher stresses), which meant that the strengthening significantly extended the uncracked state of the element's work. The same tendency was noticed in the shear capacity, which was higher in walls with GFRP strips located on the unfilled joints (arrangement A). The increase in load-bearing capacity amounted to 40%, when comparing both strengthening configurations. The stresses at characteristic moments are summarized in Table 5.

In both series the final failure of all models occurred much later that the maximum load capacity of walls was reached; unlike in the unstrengthened walls. The stresses at failure slightly decreased, which confirmed the further work stage of the elements. However, it is important to indicate that the models with strips covering the unfilled joints destroyed in a very "safe" way. The unfilled joints widened, but the existence of the sheets did not allow to excessive deformation of the elements. In places of the highest stress concentration (i.e. at the end of unfilled joints) the sheet was broken or detached from the wall surface, but the element remained in one piece (Fig. 4a). A different mode of failure was represented by the model Y-GFRP-I.B. The element was destroyed completely by two huge cracks running along the unfilled joints (Fig. 4b).

Generally, the behavior of models strengthened in set B – it is very fast cracking, negligible increase in the load capacity (compare to unstrengthened models) and rapid damage – caused that this way of strengthening with GFRP strips was considered inappropriate.

Table 5. Summary of characteristic stresses in walls strengthened using FRP system

Models	Cracking stress [N/mm^2]	Maximum stress [N/mm^2]	Failure stress [N/mm^2]
Y-GFRP-I.A-1	0.306	0.420	0.383
Y-GFRP-I.A-2	0.492	0.594	0.403
Y-GFRP-I.A-3	0.438	0.565	0.413
Mean value:	**0.412**	**0.526**	**0.400**
Y-GFRP-I.B-1	0.235	0.383	0.343

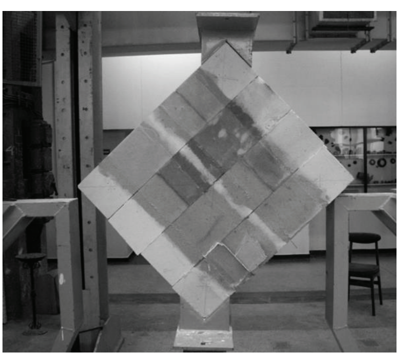
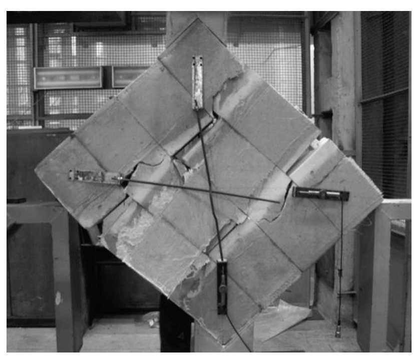
a)

b)


Fig. 4. View of the walls after failure: a) series Y-GFRP-I.A b) series Y-GFRP-I.B

3.2. FRCM SYSTEM

Table 6 shows the shear stress values calculated at cracking and failure, as well as a load capacity determined at maximum force for both series of walls strengthened using FRCM system. In both cases, a clear cracking of the walls before failure was observed. This happened at the relatively high stresses, which constitute about 90% or 70% of the maximum shear stresses for mesh type 1 and 2 respectively. Thus, double-sided application of glass mesh, regardless of its type and adhesive used, significantly extended the uncracked stage of the element's work and allowed for further work of the wall while increasing the load. From the utilisation point of view (appearance of cracks) it should be recognized, that every superficial strengthening improves the usability of sheared walls. In this respect, the weak mesh applied on a weak mortar turned out to be better than relatively strong in strength systemic solution. The models strengthened with mesh type 2 and systemic mortar cracked faster (at lower force), what should be explained by too high stiffness of the strengthening in relation to the substrate.

Table 6. Summary of the characteristic stresses in walls strengthened using FRCM system

Strengtening material	Cracking stress [N/mm^2]	Maximum stress [N/mm^2]	Failure stress [N/mm^2]
Y-GFRP.1-II-1	0.564	0.619	0.446
Y-GFRP.1-II-2	0.469	0.602	0.294
Y-GFRP.1-II-3	0.614	0.639	0.694
Mean value:	**0.558**	**0.650**	**-**
Y-GFRP.2-II-1	0.489	0.655	0.515
Y-GFRP.2-II-2	0.483	0.706	0.440
Y-GFRP.2-II-3	0.538	0.729	0.500
Mean value:	**0.503**	**0.697**	**0.485**

The reverse tendency was revealed in determining the load-bearing capacity of the walls. Of course, both FRCM systems provided a significant increase in shear capacity in comparison to unstrengthened elements, but the systemic solution turned out to be more effective. The same applies to failure of such strengthened models. The strong systemic solution does not allow to excessive deformation of the walls at final failure. The walls from Y-GFRP.2-II series, after removing the mesh indicated only small diagonal cracks on both wall surfaces (Fig. 5a). No disintegration of the masonry components was observed; the walls remained in one piece. This failure pattern was probably due to the use of very strong mortar with fiber reinforcement. The fibers limited the crack width, deformation of whole element and separation of small masonry pieces. The stresses determined at failure were about 30% lower than the maximum values, but the walls could still be considered as “safe” for people.

The walls strengthened using mesh type 1 and plastering mortar failed in a much more dangerous way, in comparison with the other series from FRCM group. Just after failure the glass mesh integrated the masonry components, but after its removing the model was completely destroyed. Two parts of the wall were separated, what is visible in Fig. 5b. The stresses determined at the final failure of the models were quite different, which resulted from the level of wall destruction. This failure pattern is totally different from the one observed in the walls from Y-GFRP.2-II series.

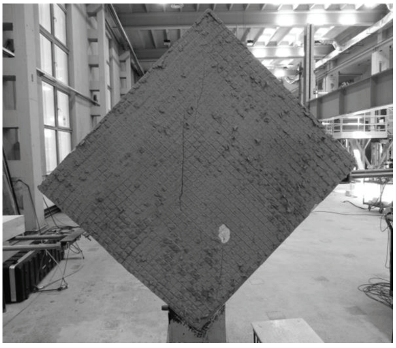
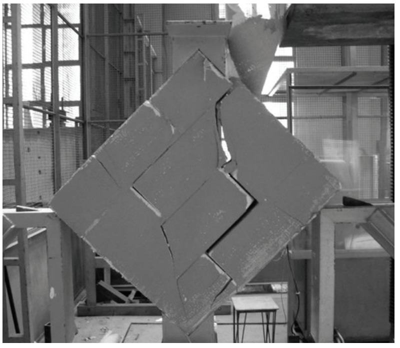
a)  b) 

Fig. 5. View of damaged walls after removing the meshes: a) series Y-GFRP.2-II, b) series Y-GFRP.1-II

3. STRENGTHENING EFFECTIVENESS

In order to evaluate the effectiveness of strengthening systems the average increases in shear capacity recorded in all tested walls are summarized in Fig. 6a. The value obtained in unstrengthened models served as reference and amounted to 1.0.

Both types of strengthening made using FRCM system provided a significant increase in shear capacity in comparison with other models. Much stronger systemic solution (type 2), comparing the properties of strengthening components – see Tab. 1 and 2, gave slightly higher values of load-bearing capacity than typical set used in plastering works (type 1). However, the difference between both full-surface applications was only 12%.

In the case of FRP system, the arrangement of GFRP strips significantly affected the load-bearing capacity of such strengthened walls. Only the covering of unfilled head joints (arrangement A) brought benefits in capacity, which increased by almost 50% in comparison with unstrengthened models. The other set of strengthening (between the head joints) brought insignificant profit and, at the same time, was characterized by an extensive failure. Strengthening made using epoxy resin (FRP), despite the use of very good materials, provided smaller increase in load capacity than every solution of the FRCM system. However, it was satisfactory anyway, considering only the local application of the strengthening.

The comparison of shear stresses when the first crack was noticed is given in Fig. 6b. The cracking (tantamount to failure) of unstrengthened walls is treated as reference value, which is 1.0.

In can be stated that only the superficial strengthening gave a measurable benefit – significant delaying of the cracking. Conversely to the increase in load capacity, the best way to prevent the premature cracking is to use the weak in strength materials (type 1). This allowed to a relatively uniform distribution of stresses in the initial phase. The use of stiff repair mortar provided a 40% increase in cracking force, when a plastering mortar even 55%. Gluing the glass sheets on the epoxy resin is the worst solution here, which can – in the most unfavorable situation (arrangement B) – accelerate the cracking of the structure.

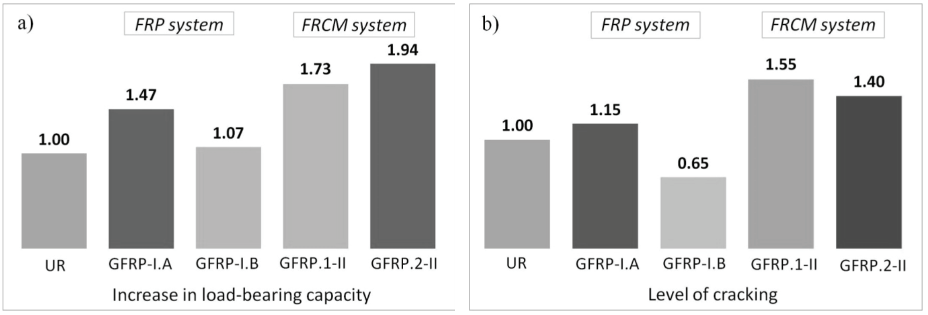


Fig. 6. Comparison of the effectiveness in: a) shear capacity, b) level of cracking

4. SUMMARY

The paper presents a reliable summary of the influence of different strengthening sets on the mechanical properties of sheared walls made using AAC blocks. Three different glass-fiber-based materials were used as strengthening, which was applied on the wall surface using epoxy resin (FRP system) or mineral mortars (FRCM system).

The comparative analysis of all tested models made it possible to formulate the main and most important conclusions summarized below.

- Application of superficial strengthening made by glass mesh and mineral mortar brings the biggest benefits both in shear capacity and delaying the cracking.
- The use of FRP system applied only locally gives a positive effects only when the strengthening is properly distributed.
- The use of strong strengthening materials not always brings the best benefits.

ACKNOWLEDGEMENT. The article presents research works partly funded by the BK-237/RB6/2018 project.

REFERENCES

1. J. Almeida, E. Pereira, J. Barros, "Assessment of overlay masonry strengthening system under in-plane monotonic and cyclic loading using the diagonal tensile test" Const. and Build. Materials 94, 851–865, 2015.
2. M. Kałuża, I. Galman, J. Kubica, C. Agneloni, „Diagonal Tensile Strength of AAC Masonry with Thin Joints Superficially Strengthened by Reinforced Using GFRP Net Plastering" Key Engineering 624, 363-370, 2014.
3. L. Kouris, T. Triantafillou, "State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)" Construction and Building Materials 188, 1221–1233, 2018.
4. A. Oskouei, A. Jafari, M. Bazli, R. Ghahri, "Effect of different retrofitting techniques on in-plane behavior of masonry wallettes" Construction and Building Materials 169, 578–590, 2018.
5. A. Rahman, T. Ueda, "In-Plane Shear Performance of Masonry Walls after Strengthening by Two Different FRPs" Journal of Composites for Construction 20(5), 2016.
6. S. Umair, M. Numada, M. Amin, K. Meguro, "Fiber reinforced polymer and polypropylene composite retrofitting technique for masonry structures" Polymers 7(5), 963–984, 2015.
7. M. Valluzzi, D. Tinazzi, C. Modena, "Shear behaviour of masonry panels strengthened with FRP laminates" Construction and Building Materials, 16, 409–416, 2002.

LIST OF FIGURES AND TABLES:

EFFEKTYWNOŚĆ WZMOCNIENIA NA ŚCINANIE ŚCIAN WYKONANYCH Z BLOCZKÓW ABK – WYNIKI BADAŃ LABORATORYJNYCH

Słowa kluczowe: konstrukcje murowane, wzmocnienie, system FRP/FRCM, ścinanie, bloczki ABK, efektywność

STRESZCZENIE:

Artykuł przedstawia porównanie efektywności powierzchniowego wzmocnienia materiałami kompozytowymi ścian wykonanych z bloczków z betonu komórkowego (ABK), które poddano ścinaniu w płaszczyźnie.
Przeprowadzono badania 14 modeli o wymiarach 805×900×240 mm, z czego 4 były niewzmocnione, a 10 wzmocniono przy użyciu materiałów na bazie włókien szklanych. Zastosowano dwa sposoby wzmocnienia: system FRP, w którym maty szklane (w dwóch ułożeniach) przyklejono do modeli przy użyciu żywicy epoksydowej i system FRCM, gdzie siatki szklane układano na zaprawach mineralnych. W drugim systemie przebadano dwa rozwiązania: nietypowe, wykorzystujące materiały do prac tynkarskich i systemowe dedykowane do wzmacniania murów. Elementy przebadano w układzie ukośnego ściskania, który odzwierciedlał rzeczywisty schemat ścinania ścian.
Zaobserwowano, że w przypadku konstrukcji niewzmocnionej pojawienie się ukośnego zarysowania było równoznaczne ze zniszczeniem muru, który rozpadał się na niezależne części. Zniszczenie to miało gwałtowny i nagły charakter, co uznano za niebezpieczny sposób zniszczenia konstrukcji.
W przypadku wzmocnienie w systemie FRP tylko przy prawidłowym ułożeniu pasm z maty szklanej – objęcie pionowymi pasami niewypełnionych spoin pionowych – uzyskano korzystny wpływ wzmocnienia na badany element. Odnotowano prawie 50% wzrost nośności muru na ścinanie, a także 15% zwiększenie siły rysującej, w odniesieniu do siły powodującej zarysowanie/zniszczenie modeli niewzmocnionych. Takie ułożenie mat szklanych gwarantowało także stosunkowo „bezpieczny" i wydłużony w czasie sposób zniszczenie konstrukcji, która po osiągnięciu maksymalnej nośności w dalszym ciągu przejmowała obciążenia, ulegając silnym odkształceniom. Klejenie mat pomiędzy niewypełnione spoiny pionowe prowadziło natomiast do dużych deformacji konstrukcji już po jej zarysowaniu. Wzrost nośności jaki uzyskano w tym schemacie wzmocnienia był natomiast pomijalny.
W przypadku wzmocnienia w systemie FRCM obydwa rozwiązania znacznie opóźniły moment zarysowania murów. Uzyskano 55% wzrost siły rysującej, w przypadku rozwiązania nietypowego i 40% przy użyciu systemowego wzmocnienia, w odniesieniu do siły, która powodowała zarysowanie/zniszczenie murów niewzmocnionych.

Odnotowano także bardzo istotny wzrost nośności na ścinanie, który wynosił prawie 75% dla materiałów tynkarskich i około 90% dla rozwiązania systemowego. Uznano, że wytrzymałość poszczególnych składników systemu wzmacniającego nie miała aż tak dużego znaczenia, gdyż przy zastosowaniu dwukrotnie silniejszych materiałów systemowych (w stosunku do materiałów tynkarskich) uzyskano jedynie 15% wzrostu nośności muru na ścinanie. Wpływ rodzaju wzmocnienia uwidocznił się natomiast przy sposobie zniszczenia modeli. Zastosowanie systemowego rozwiązania, w którym zaprawa zbrojona była dodatkowo włóknami znacznie ograniczyło uszkodzenia muru, który po zdjęciu siatki miał jedynie parę niewielkich rys ukośnych. W przypadku siatki i zaprawy tynkarskiej, po zerwaniu wzmocnienia, mur rozpadał się na niezależne fragmenty – podobnie jak mur niewzmocniony.

Generalnie, obydwa systemy wzmocnienia pozwalają na znaczący wzrost nośności konstrukcji murowanej i wydłużenie jej pracy w stanie niezarysowanym, jednak przy zastosowaniu systemowego rozwiązania FRCM korzyści są największe.

Received 07.09.2019, Revised 16.04.2020