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A REVIEW OF METHODS FOR MASONRY STRUCTURES STRENGTHENING USING HIGH-STRENGTH COMPOSITES

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Abstract. The relevance of this study stems from the need to preserve and extend the service life of a large number of existing masonry buildings. This applies both to civil structures with brick walls and to historical monuments of architectural heritage. During prolonged use, such structures are subjected to destructive atmospheric influences, leading to the degradation of bricks and mortar and a reduction in their strength. Furthermore, seismic loads pose a serious threat to their structural stability, inducing shear forces in load-bearing elements. In recent years, many buildings with masonry structures in Ukraine have been damaged as a result of massive rocket strikes, accompanied by powerful explosive loads and shock waves. In this view, the development of effective methods for strengthening masonry is an extremely important engineering task. The main objective of this work is to review and analyse structural and technological approaches to the reinforcement of masonry structures in order to select the most effective solutions for further experimental and theoretical research.

The article examines current trends in the transition from traditional strengthening methods to the use of the latest composite materials. A comparative analysis of various technologies for walls, columns, piers and beams strengthening and retrofitting has been carried out. Based on the literature reviewed, it has been demonstrated that the use of conventional fibre-reinforced polymers based on epoxy resins has a number of operational drawbacks. Organic resins prevent natural air exchange within walls due to their extremely low accumulation and debonding of the TRM (textile reinforced mortar). They are also flammable and possess excessive stiffness, which is poorly compatible with the flexible old masonry.

To address these issues, the use of a state-of-the-art strengthening system based on mineral components is justified. This technology involves replacing polymer resins with a highly plastic polymer-cement mortar, into which a reinforcing mesh is embedded. This solution radically changes the structural behaviour of the structure: instead of dangerous brittle failure, controlled plastic deformation is ensured thanks to the uniform distribution of stresses. It has been proven that the use of an inorganic matrix guarantees excellent compatibility with historical materials, offers high fire resistance and allows work to be carried out even on damp substrates.

Keywords: masonry structures; strengthening; high-strength composites.

INTRODUCTION

Currently, a significant number of masonry buildings with load-bearing brick walls are in use in Ukraine, and these are widespread in civil engineering.

Masonry structures are used in numerous buildings of architectural and historical heritage in many European cities, as well as in Ukraine (in particular in Lviv, Kyiv and Odesa).

Over the course of long-term use, brick structures are subject to the damaging effects of atmospheric conditions, which leads to a deterioration in the mechanical properties of the bricks and mortar (Fig. 1 and Fig. 2).

Fig. 1. Damaged masonry walls of historical heritage buildings situated on Rynok Square in Lviv. Photo by M. Melnyk
Рис. 1. Пошкодження мурованих стін будівель історичної спадщини на площі Ринок, м. Львів. Фото М. Мельник

Fig. 2. Bernardine Church in Lviv counterforces and walls structural damages. Photo by M. Melnyk
Рис. 2. Пошкодження конструкції контрфорсу і стін Бернардинського собору, м. Львів. Фото М. Мельник

An important factor for masonry structures is seismic activity, which gives rise to shear forces.

In recent years, many masonry buildings in Ukraine have been damaged as a result of massive rocket attacks, which are accompanied by powerful explosive charges and shock waves.

For these reasons, masonry structures often require strengthening.

In recent years, in the practice of building structures strengthening, including masonry structures, systems made of high-strength composite materials with appropriate matrices (adhesives) have been increasingly used. These systems vary in terms of the materials physical and mechanical characteristics and are constantly being improved.

AIM OF THE WORK

The main aim of this work is to review and analyse existing methods (structural and technological solutions) for the masonry structures strengthening for selection in subsequent experimental and theoretical studies.

REVIEW AND ANALYSIS OF LITERATURE

In [1], defects and diagnostic strengthening methods and strategies for historic masonry structures were analysed. It is noted that the integration of machine learning methods into diagnostics and the use of compatible composite materials allows for a significant extension the architectural monuments service life. The best results are achieved by combining traditional steel ties for overall stability and composite 'jackets for local strengthening of the most stressed areas (columns and arch heels).

Article [2] presents the results of experimental studies and analysis on stone masonry under the combined action of vertical and horizontal loads. The article systematises data on the failure nature of stone specimens under shear and identifies the decisive influence of factors such as masonry material, mortar strength, and the presence of external or internal reinforcement (carbon fibre, reinforced concrete elements, metal ties) on the elements load-bearing capacity. Analysis of this data enabled the authors to substantiate a new kinematically feasible failure mechanism under diagonal shear, which will serve as a reliable basis for calculating the strength of masonry walls using the variational method in plasticity theory.

The main objective of the research [3] was to improve the methodology for calculating the load-bearing capacity of masonry structures under the combined action of horizontal and vertical loads. For this purpose, the variational method of plasticity theory was employed.

The study of the effect of surface reinforcement using the FRCM (Fibre-Reinforced Cement Matrix) system on compressed aerated concrete masonry is presented in [4]. It is noted that two-sided reinforcement is an effective method for increasing both the load-bearing capacity and the masonry's ability to deform without brittle failure. At the same time, single-sided reinforcement is advisable for improving crack resistance and deformability, but it does not provide a significant increase in ultimate compressive strength.

Despite the high effectiveness of using innovative materials, the effectiveness of masonry structures strengthening critically depends on the quality of workmanship. This issue is the subject of a comprehensive study [5], which analyses the influence of local defects on the effectiveness of fibre-reinforced cementitious matrix (FRCM) wraps used for the compression of masonry piers and columns. The authors note that under real-world construction site conditions, the ideal application of the composite is practically impossible: defects such as uneven thickness of the mortar matrix, insufficient fibre impregnation, voids between the masonry and the mesh, or irregularities in the length of the overlaps or anchoring frequently occur.

A significant body of experimental data on the performance of classical polymer composites is presented in [6], where the load-bearing capacity of concrete block walls reinforced with epoxy-based GFRP (Glass Fibre-Reinforced Polymer) sheets was investigated. An investigation into the mechanical behaviour of the reinforced specimens showed that epoxy-fibreglass systems act as effective external tensile reinforcement. They bridge existing microcracks, prevent their propagation and radically alter the behaviour of brittle masonry. It has been established that the shear strength of the walls and their resistance to out-of-plane bending increase several-fold. Furthermore, the reinforced specimens demonstrated a significant increase in ductility, transforming the failure mechanism from sudden and brittle to gradual.

The study of the load-bearing capacity of masonry elements subjected to bending (in particular, lintels over openings and beams) is discussed in [7]. Traditionally, unreinforced masonry is practically incapable of withstanding tensile stresses from bending moments, which leads to its extremely brittle failure even with small spans. To address this issue, the authors of the article propose the use of glass-fibre-reinforced polymer (GFRP) composite strengthening. The main conclusion of this work is the experimental confirmation that strengthening with GFRP composites allows the failure mechanism of flexural masonry elements to be transformed from sudden to a more ductile and predictable one. The observed increase in the load-bearing capacity and stiffness of structures demonstrates the potential of using non-metallic composite reinforcement as an effective alternative to traditional strengthening methods.

The issue of the physical and mechanical compatibility of materials during the strengthening of historic and weakened masonry is central to the research in [8]. The test results presented in the article convincingly demonstrate that the use of highly deformable adhesives makes it possible to completely avoid the sudden detachment of reinforcement elements. Instead, the system demonstrates a significant increase in its ability to absorb load energy and a substantial increase in the ultimate strains before failure. This conclusion is of great importance for further research, as it indicates that when selecting materials for strengthening, the focus should shift from achieving maximum composite strength to ensuring its deformation compatibility with the existing masonry.

Publication [9] presents the results of experimental and theoretical studies of brick structures that were exposed to fire and strengthened by GFRP (Glass Fibre-Reinforced Polymer) meshes. The strengthening effect of the test specimens was 11.5%. The modulus of deformation of the masonry changes significantly under the influence of temperature, which substantially affects the redistribution of forces.

Comprehensive experimental and theoretical studies on the behaviour of damaged and reinforced structures are presented in the thesis [10]. The work provides a comprehensive synthesis of existing calculation methods and experimental data regarding the behaviour of structural elements with initial defects or service-induced damage. The author focuses on how exactly a breach in the material's continuity (the presence of cracks, loss of part of the cross-section) affects the redistribution of internal forces and the change in the overall structure stiffness under load. The particular value of this study lies in the detailed analysis of the stress-strain state of the 'basement-strengthening' system, taking into account the physical materials non-linearity. The paper presents the results of large-scale tests, which enabled the verification of the proposed theoretical models and calculation algorithms. It has been demonstrated that, for an adequate assessment of residual load-bearing capacity, it is necessary to consider not only the mechanical characteristics of the composite but also the loading history of the element and the extent of its degradation at the time of repair work.

The conclusions and calculation assumptions set out in [10] serve as a reliable methodological basis for further research. They confirm the need to use modern software packages (FEM) for the spatial modelling of complex non-linear processes occurring in masonry structures strengthened with high-strength composites. The application of such a comprehensive approach will enable the development of more accurate algorithms for predicting the load-bearing capacity and deformability of the structures under investigation.

For theoretical studies of the strengthening of masonry piers, the results of a numerical study [11] may be utilised, which concern the solution of physically non-linear deformation problems for massive prismatic bodies.

Article [12] outlines the general characteristics and prospects for the use of composite materials in building structures, including architectural monuments.

Important issues concerning the design resistances and strength of masonry materials are considered in [13].

Article [14] is devoted to addressing the pressing issue of repairing, retrofitting and increasing the load-bearing capacity of existing brick buildings and structures. Each strengthening method has its own advantages and disadvantages and may therefore be selected for the restoration of brickwork or the strengthening of the masonry structure as a whole. The choice of a specific strengthening method depends on the tasks at hand, and the feasibility of its use must be substantiated by appropriate calculations.

Article [15] is a comprehensive literature review devoted to methods for strengthening and modernising unreinforced masonry structures subjected to seismic and other extreme loads. The subject of the study is various technical approaches to strengthening, their effectiveness, economic feasibility, compatibility with the base materials, as well as modern methods of numerical modelling of such structures.

The article [16] provides a comprehensive review of methods for the seismic strengthening of masonry walls and piers. The subject of the study is a comparative analysis of traditional and modern retrofitting technologies, with a particular focus on innovative systems based on FRCM composite materials with an inorganic matrix. The use of special mechanical anchors successfully neutralises the risk of delamination, making FRCM one of the most effective, reliable and architecturally acceptable methods of masonry buildings seismic retrofitting for today.

Experimental studies [17] have shown that the method of combined masonry structures strengthening by using CFRP (Carbon Fibre Reinforced Polymer) together with cement-sand mortar is a highly effective and cost-effective engineering solution. It allows for a significant improvement in both the load-bearing capacity and the ductility of walls made of cement-clay interlocking bricks. The use of traditional mortar as an intermediate layer not only significantly reduces the cost of the retrofitting process but also creates favourable conditions for the materials to work together, preventing premature brittle failure of the building. The authors of the study note that such approaches have significant potential for improving the seismic resistance of buildings; however, further testing on solid bricks and concrete blocks is required for wider practical implementation.

The paper [18] notes that traditional FRP (Fibre-Reinforced Polymer) wrapping has certain drawbacks: low fire resistance, high cost and physical incompatibility of materials. The study compares two alternative techniques for brick columns strengthening: the use of basalt fibres in a BFRCM (Basalt Fibre-Reinforced Cement Matrix) and the placement of high-strength steel wires in horizontal mortar joints.

Article [19] examines the current state and prospects for the development of existing and novel methods for masonry structures strengthening. A review of current approaches to masonry strengthening indicates rapid technological development in this segment of the construction industry. Traditional intervention methods, despite their proven practical significance, often prove insufficiently effective under conditions of intense dynamic loads and strict requirements regarding the preservation of architectural heritage. Innovative systems based on high-strength composites (fibre-reinforced polymers) open up broader prospects for the restoration of wall elements, guaranteeing a significant increase in load-bearing capacity, resistance to corrosion and minimal encumbrance on the existing structure. From an engineering perspective, the use of FRP materials is the optimal solution for enhancing the reliability of structures in earthquake-prone regions and during the restoration of historic buildings. At the same time, TRM (Textile

Reinforced Mortar) systems are best suited where physical and chemical compatibility with the original masonry is a priority, whereas FRCM matrices demonstrate the highest operational efficiency in environments with high humidity.

In article [20], based on the results of finite element method calculations, accurate stress distribution diagrams relative to the principal axes were obtained both on the surface and in any cross-section of the model under study. The simulation results scientifically substantiated the feasibility and high efficiency of using steel hoops to strengthening damaged brick columns, which is a critically important condition for the safe installation of built-in civil defence structures in existing buildings.

Article [21] is a review study devoted to methods for strengthening composite (framed) masonry structures with the aim of increasing their resistance to loads acting in the plane of the wall. The subject of the study is a variety of technical approaches to retrofitting, covering the use of both traditional materials (e.g. ferrocement and steel mesh) and modern polymer composites reinforced with various types of fibres.

The main types and systems of masonry structures strengthening using high-strength composites, along with the main research findings, are presented in Table 1.

Table 1. Structural types and primary research findings.
Табл.1. Типи конструкції та основні результати досліджень.

№	Reference number, [№]	Type of structure studied	Type and systems of reinforcement material	Main research results	
				Experimental	Theoretical
1	[2], [3], [16]	Masonry walls and buttresses	CFRP, GFRP, FRCM, steel ties/stirrups, shotcrete concrete	Strength increase: from composites: 30–100%; from steel tendons: 90%; transition to ductile failure.	Kinematic models of plastic failure have been developed, the three-line behaviour of FRCM has been described, and the anchoring mechanism has been substantiated.
2	[5], [14], [18]	Masonry columns and pillars	FRCM, steel wires in joints, brick stirrups with anchors	Strength: FRCM: +44%; for wires: +25%; deformation properties for wires: +101%.	The mechanics of brick clip behaviour have been described, and a non-linear model of deformation has been developed.
3	[1], [15]	Historic buildings and unreinforced masonry	FRCM, SRG, FRP, shotcrete concreate, metal and timber ties	Shear resistance increases by 1.1–3 times; axial strength up to +200%; spatial stiffness and structural integrity of the building are improved.	Models have been applied for crack detection (98% accuracy) and the masonry reinforcement contact zone has been modelled.
4	[4], [6], [17]	Walls made of precast blocks (aerated concrete, concrete blocks, interlocking bricks)	FRP on an epoxy or cement matrix, FRCM	Significant increase in the strength of concrete (5–10 times) and brick (up to +171%), as well as a 50% increase in the transverse deformation of aerated concrete.	Strength equations have been developed, calculations have been performed according to Eurocode, and combined reinforcement schemes have been justified.

Table 1. (continued)
Табл.1. (продовження)

5	[8], [21]	Brickwork using highly elastic composites	Natural and FRP fibres on flexible adhesive, WRCM, ECC	Flexible adhesive increases adhesion by 76%; ECC – +250% in strength, WRCM – up to 150%; energy absorption increases significantly.	Reduction of stress concentrations using flexible adhesives and a balance of strength and deformability in WRCM and FRP systems.
6	[7]	Masonry ceramic beams	Combined reinforcement (A400+A1000) + GFRP	Pronounced plastic nature of failure, effective utilisation of the strength reserves of both types of reinforcement.	The actual agreement between the experimental and design load-bearing capacity of the beams is within 8.8%.

In this table: FRP (Fibre-Reinforced Polymer) - Fibre-reinforced polymer (adhesive, most commonly epoxy resin). These are divided into:

- CFRP (Carbon Fibre-Reinforced Polymer) – carbon fibre-reinforced;
- GFRP (Glass Fibre-Reinforced Polymer) – glass fibre-reinforced;
- BFRP (Basalt Fibre-Reinforced Polymer) – reinforced with basalt fibre;
- BBFRP (Bamboo Fibre-Reinforced Polymer) – reinforced with bamboo fibre.

The main drawback of FRP is that epoxy resin does not “breathe”; systems have therefore been developed that use a special cementitious or lime-based mortar instead of chemical resin:

- FRCM (Fibre-Reinforced Cementitious Matrix) – a system based on an inorganic matrix. This is a special plaster into which a strong mesh is embedded. This system is perfectly compatible with old brickwork and allows the wall to 'breathe".
- SRG (Steel Reinforced Grout) – steel reinforcement in the mortar. Instead of composite mesh, strips woven from ultra-strong microscopic steel cables are embedded into the cement mortar.
- WRCM (Wire Reinforced Cementitious Matrix) – ferrocement. This is the traditional and oldest method: ordinary welded metal mesh (made of rebar or wire), which is nailed to the wall and covered with standard cement-sand mortar.
- ECC (Engineered Cementitious Composites) engineered (or high-tech) cementitious composites. This is commonly referred to as “flexible concrete”. It is a special cement mixture into which millions of tiny polymer fibres (microfibres) are mixed. Whereas ordinary concrete develops a single large crack and splits under load, ECC stretches, forming thousands of microcracks (as thin as a hair), and does not fail.

SUBSTANTIATION OF THE NOVELTY AND ADVANTAGES OF THE SIKA MONOTOP-722 MUR + SIKAWRAP-340G GRID AR SYSTEM

This system belongs to the class of FRCM (Fibre-Reinforced Cementitious Matrix) or TRM (Textile Reinforced Mortar) composites. It has been specifically designed to address the issues that arose when using traditional FRP systems (fibre-reinforced polymers based on epoxy resins) on masonry structures [26,27].

A detailed analysis of its differences, innovations and advantages is provided below:

Fundamental difference: an inorganic matrix instead of epoxy resin

What is new: traditional composites (FRP) use organic polymer matrices (epoxy resins).

In contrast, the SIKA system uses an inorganic cementitious matrix, Sika MonoTop-722 Mur – a single-component fibre-reinforced mortar with reactive pozzolanic additives.

Why is this better: as noted in previous articles (for example, in review [16]), epoxy resins are vapour-impermeable, which is critical for old brick walls, as moisture becomes trapped inside, leading to the deterioration of the substrate and delamination of the strengthening. The SIKA matrix has high vapour permeability. This allows the masonry to 'breathe and ensures excellent physical and chemical compatibility with brick, tuff and natural stone.

Specialised protection for the reinforcing fibre

What makes it different: the system uses SikaWrap-340G Grid AR mesh. This is a bidirectional mesh made of alkali-resistant (AR) glass.

What's new: Glass fibre is vulnerable to the alkaline environment of cement mortars. To solve this problem, SIKA coats its mesh with a special SBR latex coating (SBR-Latex coating).

Why it is better: This ensures that the reinforcement mesh will not degrade over time within the cement matrix of the mortar, retaining its high mechanical properties.

High deformability (plasticity)

What's the difference: Epoxy adhesives are extremely rigid. Sika MonoTop-722 Mur is classified as a high-ductility cementitious mortar.

Why it is better: According to previous studies (in particular, article [8]), the use of rigid adhesives on weak masonry creates dangerous stress concentration peaks, leading to premature detachment of the composite together with the brick layer. SIKA's ductile mortar distributes stress more evenly between the mesh and the wall, preventing brittle failure.

Thermal stability and fire resistance

What's the difference: Organic resins in FRP systems soften and lose strength at relatively low temperatures (often as low as 60-80°C) and are also flammable.

Why it is better: SIKA's inorganic matrix is classified as Euroclass A2 for reaction to fire. It performs consistently across a wide operating temperature range from -20°C to +100°C, making it significantly safer and more durable.

Technological installation and resistance to humidity

What's the difference: Epoxy resins require a perfectly dry surface for application and complex chemical mixing processes.

Why it's better: SIKA MonoTop-722 Mur can be easily prepared and applied using traditional plastering techniques. Most importantly, it can be applied even to damp surfaces, making it ideal for the restoration of old buildings, basements or structures in challenging climatic conditions.

Seismic resistance

This system has been successfully tested for seismic retrofitting. It provides the necessary shear and flexural strength to withstand loads both in-plane and out-of-plane, whilst adding virtually no weight or stiffness to the structure (the system is only about 10 mm thick).

Thus, the main advantage and innovation of the SIKA FRCM system lies in the synergy of the high strength of modern fibres and the ideal compatibility of traditional cementitious materials, which eliminates the main drawbacks of classic polymer reinforcement.

When calculating and designing reinforcement for eccentrically compressed walls, it is necessary to identify the zones of maximum compressive stresses (Fig. 3).

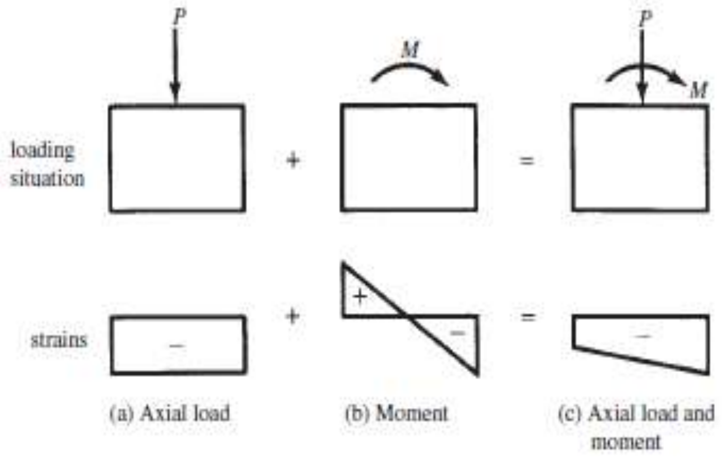

Fig. 3. Calculation scheme for eccentrically compressed walls.
Рис. 3. До розрахунку позацентрово-стиснутих простінків

Under these conditions, the wall may function under eccentric compression, but only within the combinations of axial loads and bending moments in the section that remains under compression [27].

With a small bending moment acting on the wall (i.e. when the eccentricity is small), the entire element will be in compression, but the stress on one side will be greater than on the other. The maximum compressive strain in the wall will be 0,35%, and failure will occur either due to crushing of the compressed zone of the masonry, or due to decompression of the partition on the opposite side.

As the axial load applied to the wall changes, the moment that the wall can withstand also changes. Therefore, the effect of the axial load is extremely important, as it will alter the maximum permissible bending moment. Consequently, several combinations are possible (axial bending).

All these combinations can be calculated in accordance with the compatibility of deformations and the equilibrium of forces and moments, and plotted as an interaction diagram. The interior of the diagram will show the various combinations of axial loads and bending moments that the panel can withstand.

CONCLUSIONS

1. In the practice of reinforcing masonry structures (walls, buttress, columns, etc.), high-strength composites and adhesives made from various materials are increasingly being used, including in Ukraine.
2. The literature review conducted has enabled the grouping of various reinforcement systems and the analysis of their positive and negative aspects for consideration in future research.
3. One of the most suitable systems for masonry structures reinforcing is the new FRCM composite system from SIKA, which possesses a few important structural and operational characteristics and can be used for new experimental and theoretical studies of the stress-strain state with various types and nature of damage to brickwork.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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ОГЛЯД СПОСОБІВ ПІДСИЛЕННЯ МУРОВАНИХ КОНСТРУКЦІЙ ВИСОКОМІЦНИМИ КОМПОЗИТАМИ

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Анотація. Актуальність цього дослідження зумовлена необхідністю збереження та продовження життєвого циклу великої кількості існуючих мурованих будівель. Це стосується як споруд цивільного призначення з цегляними стінами, так й історичних пам'яток архітектурної спадщини. Протягом тривалої експлуатації такі об'єкти зазнають руйнівного атмосферного впливу, що призводить до деградації цегли та розчину і зниження їхньої міцності. Крім того, серйозну небезпеку для їхньої просторової стійкості становлять сейсмічні навантаження, які викликають зсувні зусилля у несучих елементах. В останні роки в Україні багато будівель з мурованими конструкціями пошкоджено внаслідок масованих ракетних ударів, що супроводжуються потужними вибуховими навантаженнями та дією ударної хвилі. З огляду на це, обґрунтування дієвих методів зміцнення мурування є вкрай важливим інженерним завданням.

Основною метою роботи є огляд та аналіз конструктивних і технологічних підходів до підсилення мурованих конструкцій для вибору найефективніших рішень у подальших експериментальних та теоретичних дослідженнях. У статті розглядаються сучасні тенденції переходу від традиційних способів підсилення до використання новітніх композитних матеріалів.

Проведено порівняльний аналіз різноманітних технологій посилення стін, колон, стовпів та балок. На основі опрацьованої літератури доведено, що використання класичних полімерів, армованих волокнами на основі епоксидних смол, має низку експлуатаційних недоліків. Органічні смоли унеможливлюють природний повітрообмін у стінах через вкрай низьку паропроникність, що провокує накопичення вологи та відшарування підсилюючого шару. Вони також є горючими і мають надмірну жорсткість, яка погано сумісна з податливими старими муруваннями.

Для вирішення цих проблем обґрунтовано доцільність застосування новітньої системи підсилення на основі мінеральних компонентів. Ця технологія передбачає заміну полімерних смол на високопластичний полімер-цементний розчин, у який вкладається армуюча сітка. Таке рішення кардинально змінює механіку роботи конструкції: замість небезпечного крихкого руйнування забезпечується контрольоване пластичне деформування завдяки рівномірному розподілу напружень. Доведено, що використання неорганічної основи гарантує відмінну сумісність з історичними матеріалами, має високу стійкість до вогню та дозволяє виконувати роботи навіть на вологих основах.

Ключові слова: муровані конструкції; підсилення; високоміцні композити.

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