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Review paper

Composite materials in conservation of historical buildings: examples of applications

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Abstract: Traditional methods of restoring historical buildings typically consisted in replacing the damaged elements or additional steel and reinforced concrete elements were inserted into the old structure. They significantly interfered with the statics and aesthetics of buildings. Current composite materials used in restoration damage the old structure only slightly and can usually be removed in the future. Due to these advantages they comply with the conservation law in force. This paper presents a few examples of practical applications of composites the authors have designed for structural reinforcement and protection of historical buildings. Repairs of columns, vaults, masonry walls, stone facades and wooden beams with the use of steel screw-shaped bars and high strength fibres in epoxy resin or cement matrix were presented. Problems of ensuring the proper bond of the composite to the old substrate and insufficient coverage of the fibers with the cement matrix were considered. Although the threats and structural damages which occur in most historical buildings tend to be similar, individual design solutions are required in each case. Historical investigation and detailed measurement of geometry and deflections have to be made before choosing the appropriate method of reinforcing the old structure. It can be predicted that prestressing composite materials used for historical structures will also be applied.

Keywords: composite materials, historical buildings, structural reinforcements

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1. Introduction

Composite materials also known as composites are materials of heterogeneous structure produced from two or more constituent materials with notably dissimilar properties. The individual components remain separate and distinct within the finished structure. Usually one of components makes a continuous matrix which guarantees consistency and flexibility. It surrounds the dispersed phase, i.e. structural component, ensuring high strength.

Composites are applied as construction materials in many technical fields including the building industry. Plywood and wattle and daub building method which consisted of timber lattice filled with clay mixed with straw are the examples of composites known for centuries. Reinforced concrete is a composite which has been widely used from the beginning of 20th century. Nowadays also especially formed bars are used for repairing and merging of cracked masonry walls. Composite materials made of highly strong fibres have existed for several dozen years. They are very durable and chemically resistant [1].

Traditional building reinforcement methods typically entailed replacing or restoring the degraded materials used in the structure with the aim of reconstructing the original section and continuity thus increasing the sections to ensure greater load bearing capacity and safety. In the past iron elements like rods and hoops were inserted into the masonry. In more recent times reinforced concrete pillars and beams were confined in historical walls or in the thickness of finishing layers [2]. Such applications, which are difficult to perform and significantly interfere with the statics and aesthetics of buildings, also demonstrate poor durability to maintain the effectiveness of the reinforcement over time. They are disadvantageous in the case of historical buildings.

Currently, more and more accurate research methods are used for building research and numerical models are analysed in order to assess the threats affecting historical buildings better [3]. It also requires the use of new materials for repairs. Such features like excellent mechanical properties, small dimensions and lightness, make composite materials especially useful for repairing historical buildings. Composites bonded to the stone, brickwork or timber surfaces reduce stress caused by bending, shearing and tension [4–6]. Furthermore, composites damage the structure of old buildings only slightly and can usually be removed in the future. Due to these advantages composites comply with the conservation law in force [7].

This paper presents a few examples of practical applications of composites the authors have designed for structural reinforcement of columns, vaults, masonry walls, balconies, stone facades and timber rafter framings.

2. Contemporary composite materials

Masonry structures may be reinforced with bars embedded into mortar so that all the materials would act together in resisting action effects [8]. Nowadays modern steel processing methods make it possible to obtain special properties of rods which can be inserted invisibly in historical masonry. Spiral-shaped rods with a diameter from 3 to 10 mm may be placed in pre-drilled holes even without mortar or pasted in joints between bricks. Spiral-shaped rods are rolled from a plain stainless steel round wire, the fins are hardened to a very high level whilst the core remains relatively soft. The tension induced by the twisting process also ensures that any impurities in the base material are detected early, helping to produce a safer product. The tensile strength of the base material is more than doubled during this manufacturing process [9].

The first composite reinforcing bars with carbon and aramid fibres in resin matrix were applied in Japan in the 80s of 20th century, later in the 90s in Canada. Now they are commonly available. They are nine times lighter than steel bars of the same strength and corrosion resistant and durable [10].

Most of fibres used in composite bars, plates and fabrics have a diameter 2–16 µm. Very fin and strong fibres owe their properties to an ordered internal molecular structure. They are made of natural raw materials, e.g. glass, silicon and carbon or obtained synthetically from polymers e.g. aramid known as kevlar and PBO (Poliparaphenyl Benzobis Oxazole) fibres. The PBO fibres, compared with carbon fibres, have tensile strength greater than 40% and elastic modulus greater than 15% [11] (Table 1).

Table 1. Properties of structural steel and some fibres [11]

	Specific mass [g/cm^3]	Young modulus [GPa]	Tensile strength [MPa]
structural steel	7.85	210	200–700
steel fibre	7.85	210	4 000
glass fibre	2.54	72	3 600
aramid fibre (kevlar)	1.44	112	2 800
carbon fibre	1.75	240	4 100
PBO fibre	1.56	270	5 800

Application of composites for repairing old buildings began about 25 years ago from FRP (Fibre Reinforced Polymer) strengthening systems which consisted of long fibres of high mechanical performance and epoxy resin matrix which works as adhesive between the fibres and the substrate allowing the transfer of stress from the structure to fibres. A lot of research has been carried out on this system which was successfully used in conservation of many historical masonry structures [12]. For several years FRCM (Fibre Reinforced Cementitious Matrix) systems have been available. In this case inorganic matrix replaced the epoxy resins of traditional FRP systems. The FRCM system overcomes the limits concerning safety, reliability and durability of the mechanical performance of FRP systems. The main benefits of FRCM systems are applicability on dump substrates, fire resistance identical to that of the substrate, good resistance to high temperature, water vapor permeability and ease of application [13, 14].

The ability of both systems to increase the load-carrying capacity of the structural element to which they are applied depends on their bonding behaviour. Debonding of the composite from masonry is a brittle phenomenon, which typically occurs prior to exploiting the full tensile capacity of the composite. In FRP systems the thin layer of the substrate is usually thorn off together with the composite [15], while in FRCM the debonding occurs at the fibres/matrix interface after a considerable fibres/matrix slip. The best results were obtained for PBO fibres [16]. The substrate on which the composite is applied may not play a key role in the design of the strengthening system, which is an interesting aspect of this composite. Moreover, the debonding process at the matrix–fibre interface is complicated by the *telescopic* behaviour observed in a fibre bundle where the core fibres have a different mechanism of stress transfer with respect to the outer fibres, mainly due to the different impregnation of the fibres by the matrix. Values of final debonding strength of FRCM systems have been already estimated with mechanical models and validated experimentally [17–19]. Practical applications on a historic structure always require an individual approach.

3. Columns and pillars

Stone and masonry columns and pillars are often subject to damage that can lead not only to their own destruction but also of the parts of the building supported by them. Damage is caused by tensile stresses transverse to the column axis which occur in the uniaxial compression state. Cracks occur when stresses exceed the low tensile strength of old brick masonry. In solid stone elements cracks start occurring in natural internal defects of material.

In the past steel hoops were installed on the stone column shafts and lattices made of welded hot-rolled steel angles and flats were fixed around masonry pillars (Fig. 1).

Prestressing was used as well. Overloaded and cracked pillar carrying the vault of the church in Wiślica, Poland, was repaired in the 60s of 20th century. The stone shaft of pillar was spirally wrapped with wire of high strength, which was then tensioned [2]. The idea of such structures was to withstand dangerous horizontal tensile forces occurring during uniaxial compression but they were too visible. When covered with casing they significantly changed the original form of column. Besides, the steel parts corroded easily.

Most of these disadvantages can be avoided by applying composite materials [13]. Stone columns of arcades in the courtyard of the Baranów Sandomierski Castle were reinforced with bands of FRP carbon fibre mesh (Fig. 2a). In such a way old unsightly hoops were eliminated. Thin composite bands were pasted in shallow furrows cut in stone. Then places of repair were filled with mortar matching the colour of the original stone. They are completely invisible now. Brick pillars with a rectangular or polygonal section may be reinforced in similar way, too (Fig. 2b). Another method of reinforcing brick masonry pillars is inserting transversal steel or composite bars (Fig. 2c). Composite bands or rebars embedded into mortar of masonry should withstand horizontal tensile stresses the value of which can be estimated from the Poisson's ratio $\nu = 0.2$ for lime stone and brick mortar [8].

(a) (b)

Fig. 1. Traditional reinforcements of: a) stone columns (Castle of Baranów Sandomierski), b) brick masonry pillars (gallery of tenement house in Cracow, Gołębia street)

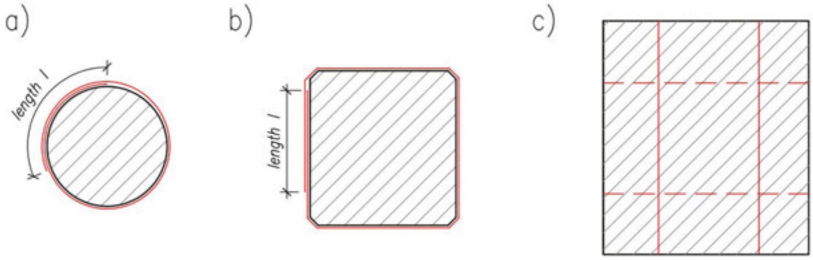

Fig. 2. Sections of stone column (a) and brick pillar (b) reinforced with composite bands (length *l* should ensure the continuity of fibres), section of brick pillar (c) reinforced with rebars embedded into mortar

4. Vaults

Threat to the security of historical vault may be caused by its improper original shape that entails eccentricity of loads and tensile stresses in some sections of the vault. Sometimes it may happen that deformations of vault occur because of horizontal displacement of supporting walls and pillars or new additional loads. Concentrated and not symmetrical loads from floors are especially dangerous. Cracks occur in places where hinges in arch of vault are formed. A stable arch may develop up to three hinges, but four hinges or more will lead to collapse (Fig. 3).

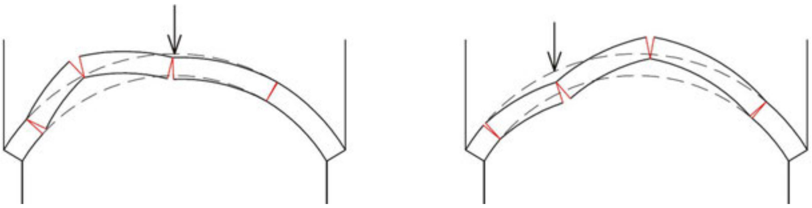

Fig. 3. When load of vault is movable cracks may occur in different zones of the upper and lower surface

Traditional method of protecting the vault was to put a bearing reinforced concrete slab on its top and anchor it to the vault (Fig. 4). Loads of inter-storey vaults were reduced by means of additional steel and concrete floors. Both methods result not only in the growth of the load of walls and foundation but they also significantly interfere with the historical structure. Consequently, they are not willingly accepted by the conservation authorities.

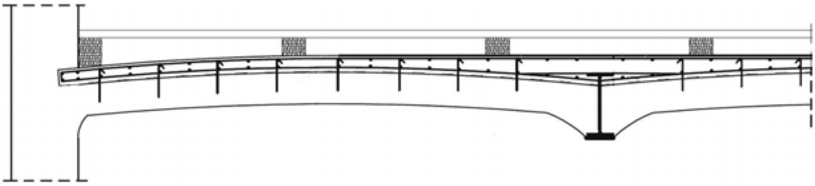

Fig. 4. School in Gorlice. Segmental barrel vault over the ground floor. First project of reinforcement with reinforced concrete slab 7 cm thick anchored to the vault

Hinge and formation of cracks can be prevented and vault can be strengthened by increasing the load capacity of the vault section. Improving the tensile strength of old brick masonry is not possible, but similar effect can be obtained if the composite strong mesh is stuck on the tensioned side of the vault. Taking into consideration all combinations of loads acting on the floor mesh should be stuck on the whole upper and lower surface of vault (Fig. 3). Such way of reinforcing the segmental barrel vault was applied in a school in Gorlice where both sides of the vault were uncovered during restoration works (Fig. 5). Location of thrust line in the arch of vault and values of stresses in critical sections were found on the basis of diagrams of bending moments and axial forces. The calculations showed that reinforcing both sides of the shell with strips of composite mesh 0.5 m wide in 1.0 m spacings is sufficient. Thus the initially designed heavy reinforced concrete slab did not have to be applied. Transversal steel strips seen on Fig. 5 protect the mesh against detachment from the bottom side of the vault. Strips are connected with stainless steel screws through the vault. Currently composite bundles of fibres are available and can be used for this purpose [11].

Fig. 5. School in Gorlice. Reinforcement of segmental barrel vault with FRP composite mesh. Bottom (left) and upper (right) sides of vault

However, there is usually only one side of the vault available for sticking the mesh either because the whole building cannot be renovated at the same time or the bottom surface of the vault is decorated with paintings or stucco. It was the case of the Royal Palace in Łobzów where the Faculty of Architecture of Cracow University of Technology is currently located. The ground floor rooms were restored only when the works on the first floor had been completed. Therefore strips of mesh were stuck crosswise the cracks only on the bottom side of the vaults. In such a way only some of the hinges in critical sections with cracks on visible side of vault were eliminated, but it turned out to be sufficient for the security of the vault. The repair was successful and cracks did not reappear (Fig. 6).

Fig. 6. Royal Palace in Łobzów, Cracow. The vault before (left) and after (right) renovation

Composite reinforcement A_m of the critical section of vault and its load capacity may be found on the basis of the model of eccentrically loaded masonry section presented in Fig. 7. Strength of historical masonry f_{cd} is estimated using rules and formulas from current norm [8], tensile strength of composite system f_m depends on possibilities to anchor the fibres of mesh.

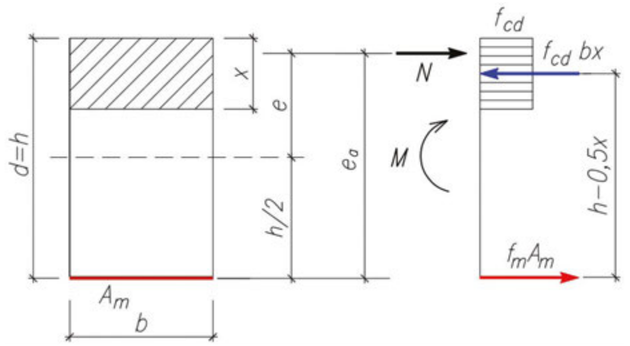

Fig. 7. Eccentrically loaded section of vault ($e = M/N$) reinforced with composite

Location of neutral axis of the section is found from Eq. (4.1):

(4.1) $$f_{cd}(e_a - h + 0.5x) \cdot b \cdot x - f_m \cdot A_m \cdot e_a = 0; \quad x \leq 0.5h$$

Load capacity of the strengthened section may be found using equation of balance of moments of forces relative to the axis of composite reinforcement Eq. (4.2):

(4.2) $$N \cdot e_a \leq f_{cd} \cdot b \cdot x \cdot (h - 0.5x)$$

and equation of balance of forces Eq. (4.3):

(4.3) $$N \leq f_{cd} \cdot b \cdot x - f_m \cdot A_m$$

5. Bracing the walls

Walls of masonry buildings require bracings in order to withstand horizontal tensile forces from differential settlement of foundations or thrust forces of vaults. Beams surrounding the reinforced concrete floors fulfil this role in modern buildings. Traditional timber beam-framed floors are not sufficiently effective braces for masonry walls. This structural defect becomes apparent in the formation of cracks of inter-window strips (Fig. 8a). In the past during renovation works original timber floors existing in historical buildings were commonly replaced by steel and reinforced concrete floors type WPS, and later by corrugated steel floor decking with concrete topping. Such structures ensured adequate stiffening of the building. Nowadays timber floors are removed only if old beams have been completely destroyed by biological corrosion. Wooden beams can be strengthened to the assumed bearing capacity and required fire resistance provided by lightweight layers of fireproof materials. When a major renovation of the building interior is performed additional bond beams made of steel angles may be fixed to wooden beams and walls (Fig. 8b).

If conservation considerations concerning protection of elements decorating the facade make it possible, bond beams bracing the masonry structure of a building may be placed

(a) (b)

Fig. 8. Tenement house in Łódź, Żeromskiego street: a) cracks on elevation and b) steel bond beam

on the outer side of the walls. In the past steel sections were hidden in carved furrows [2]. Nowadays similar beams are made of strips of composite mash bond outside the wall and covered with plaster [11–13]. They do not interfere with structure of the wall at all.

High walls supporting vaults and the vaults themselves are usually damaged because of insufficient rigidity and bearing capacity of elements withstanding the thrust forces from vaults. It is necessary to ensure stability of the building structure and eliminate tensile stresses causing cracking of brick masonry before undertaking restoration works on the interior and facade decoration.

At the beginning of 21st century design works were undertaken on conservation of synagogue in Słonim, Belarus built in 1642. The building was covered with a system of barrel and cross vaults supported on perimeter walls and central bima. The haunch of the vault was filled with brick rubble. Cracks of vaults and arches above windows (Fig. 9) showed that the thrust forces from the vault were the source of threat to the stability of the building structure.

Static calculation of the structural system of vaults with upper strip of walls above windows supporting them proved that excessive tensile stresses existed in that zone. The strengthening system which was designed consisted of two pairs of steel cables holding the walls together on the top of the inter-window pillars. Three-span brick masonry beams reinforced with composite FRP carbon fibres plates were created in each wall. Such a new static system replaced the original system of one span beams without reinforcement. Inter-window pillars were strengthened with FRP carbon fibre plates stuck on the outer side. Other FRP plates bond on the whole perimeter of building eliminated the negative impact of horizontal components of reactive forces from the vault flowing into corners (Fig. 10). In such a way, having changed the static system of the structure supporting the vault, tensile stresses causing cracking of walls were significantly reduced. Thanks to the application of small-size composite materials it was achieved with minimal structural interference in the historical wall.

(a) (b)

Fig. 9. Synagogue in Słonim, Belarus: a) cracks of the vault and b) the arch above window

Decision concerning reinforcement of vault with composite mesh stuck on its bottom side depends on the result of investigation of polychrome decorating the vault. Whereas sticking the mesh on the upper side may be done if the brick rubble has been removed from the vault.

In a similar way composite materials were used in order to stabilize the walls supporting the dome of “Baszta Boska” in Krasiczyn, the dome of church in Ląd Abbey and the lantern of Poland’s biggest dome of a baroque church in Gostyń near Poznań.

6. Stone facades

Stone facades are aesthetic and durable thanks to the properties of natural material. Air pollution in the city centres causes contamination and chemical corrosion of the surface of stone. Every few decades stone facades require cleaning and maintenance. Besides, structural damage occurs as well and it can lead to the total destruction of parts of the facade. Stone elements may fall down and threaten the safety of people in the street. Stone cladding panels used to be attached simply by means of cement mortar poured into the gap between the wall and the panel. After sometime they get detached due to the freezing of water penetrating into gaps through leaks in joints. Stone elements were sometimes

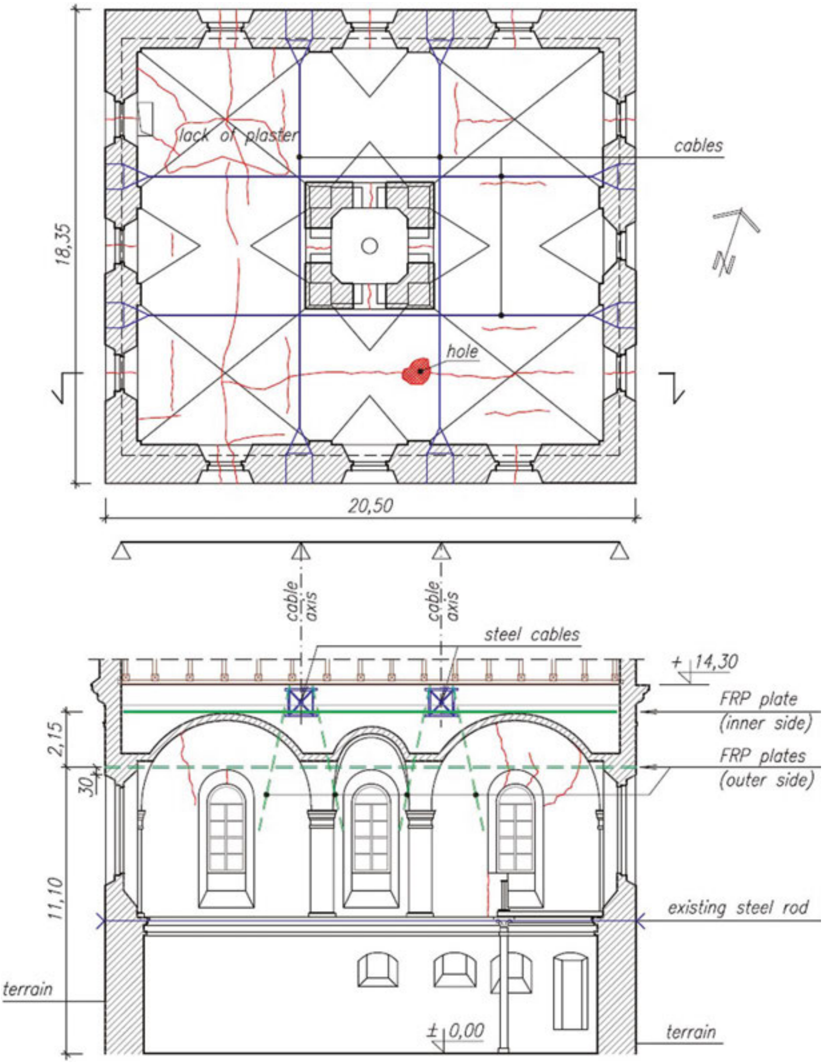

Fig. 10. Synagogue in Słonim, Belarus. Design of strengthening the structure supporting the vault

fastened with steel anchors which corroded over time causing cracking and braking of stone.

The City Hall in Warsaw in Kredytowa street built in 1905–1909 has beautiful, richly decorated stone facades. There are six balconies of stone structure on the second and third floors (Fig. 11a). The stone slabs of the balconies have been supported with stone brackets. Only the upper floors of the building were destroyed during the Warsaw Uprising in 1944. The lower storeys with the original stonework have been preserved.

(a) (b)

Fig. 11. Warsaw, Kredytowa street 3: a) stone balcony and b) bracket fallen down from the facade

One of stone brackets from the balcony on the second floor fell down a few years ago. Damage of stone panels could be observed, too. A close inspection showed that the cause of the damage was the corrosion of steel anchors fastening stone elements to the wall (Fig. 11b).

Renovation works have been undertaken, including the facades of the building. It was of fundamental importance to ensure safety through the implementation of structural measures for durability of fastenings of wall panels and balconies. It had to take place before the actual conservation works were carried out. The first project involved dismantling the balconies and reassembling them on a new structure made of steel hot-rolled sections. Our replacement project applied FRP carbon fibre plates and steel screw bars (Figs. 12, 13). It was successfully applied as permanent protection for all balconies of the front facade. Stone cladding panels in danger of falling off were anchored to the wall with steel screw-shaped rods placed in two corners of each panel.

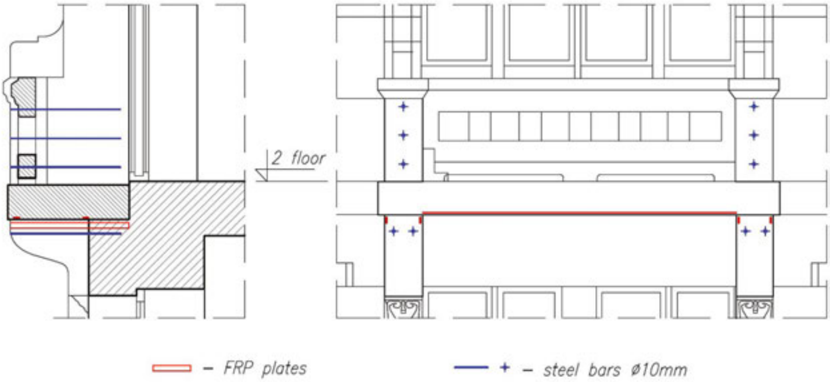

Fig. 12. Warsaw, Kredytowa street 3. Design of strengthening and protecting stone balconies. Section (left) and elevation (right) of balcony

Fig. 13. Warsaw, Kredytowa street, 3. Strengthening elements covered with colour mortar

7. Timber beams

Some attempts were made to strengthen timber beams using composite materials [20]. Laboratory tests were carried out on small samples [21] and on full scale beams 20 ×20 ×400 cm reinforced with carbon fibre sheets or bars bond in grooves cut in tension zone of the section. Results showed increases in flexural capacity up to 60.3% in the case of composite sheets and 50.2% in the case of composite bars compared with unreinforced beams. Maximum increase of stiffness was 20–30% depending on the type of reinforcement [22]. The test to estimate the influence of reinforcing with composite mesh on the bending strength and modulus of elasticity of fir wood beams was carried out at Kielce University of Technology. Beams with cross-sectional dimensions 8×8 cm and length of 160 cm were reinforced with PBO mesh bond to the bottom tensile side. The results indicated increase of bearing capacity of beams reinforced in this way by 56%, the modulus of elasticity by 4.9% and the deflection of beam at the time of destruction by 77.5% [23].

Within the framework of a research project carried out at the Cracow University of Technology non-destructive strength tests of wooden elements from historical rafter framing of the barracks for prisoners in the Auschwitz II – Birkenau Extermination Camp were carried out [24]. Beams had square and circular sections, numerous wood defects and corrosion damage. Original rafters from the roof structure were treated as historical. For this reason, bending attempts were not carried out to destruction, but only to obtain beam deflection 1/150 of span $L = 4.00$ m (26.7 mm). Bearings for beams were assumed in the same points they had been supported in the original rafter framings (Fig. 14a). First, the beams were tested prior to reinforcing. The second stage of the research concerned the strengthening by sticking the carbon fibre plate in 6×25 mm slot milled on the tensile side of original rafters (Fig. 14b).

Reinforcement caused old rafters reached the assumed deflection 26.7 mm under a load about 5% bigger than before. The effectiveness of reinforcing wooden beams with FRP plates depended very much on existing corrosion damage of wood and on the possibility of supplementing the cross-sections with additional elements. An important observation was that all carbon fibre plates did not detach from the wood.

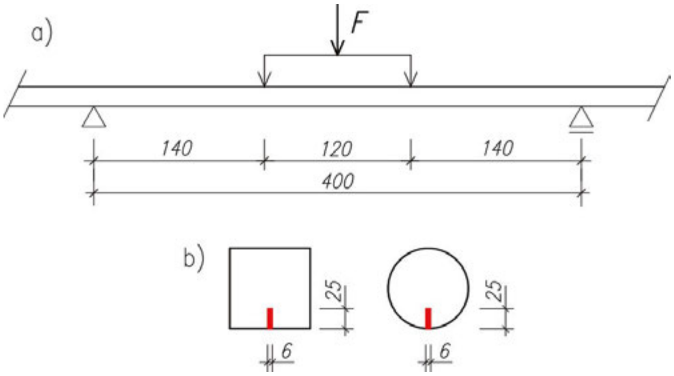

Fig. 14. Investigation of rafters from the roof of the barracks in Camp Auschwitz II – Birkenau, a) static system of the four points bending test, b) sections of the rafters reinforced with FRP carbon fibre plate

In this case measurement of final deflections of the reinforced beams at the time of destruction was not possible. Only on the basis of the previous destructive testing the significant impact of composite reinforcement on the safety of the structure can be predicted.

8. Conclusion

All examples of the applications of composite materials in historical buildings presented above confirm their efficiency in executed repairs and also compliance with the conservation law in force.

Although similar threats and structural damages occur in most historical buildings, individual design solutions are required in each case. Historical investigation and detailed measurement of geometry and deflections have to be made before choosing the appropriate method of reinforcing an old structure. Other factors affecting the stability of the building, mainly the foundation, the existing soil and water conditions are also necessary. Harmful factors should be eliminated before undertaking repair with composite materials.

As prestressing composite materials used for contemporary reinforced concrete structures has proved to be effective it is applied more and more often in the building industry. It can be predicted that prestressing composite materials used for historical structures will also be applied.

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Materiały kompozytowe w konserwacji budynków historycznych: przykłady zastosowań

Słowa kluczowe: konserwacja budynków, materiały kompozytowe, wzmocnienia konstrukcyjne

Streszczenie:

Materiały kompozytowe, zwane też kompozytami, to materiały o niejednorodnej strukturze, złożone z dwóch lub więcej komponentów o różnych właściwościach. Kompozyty mają zastosowanie w wielu dziedzinach techniki, w tym również w budownictwie. Od kilkudziesięciu lat istnieją materiały kompozytowe zawierające włókna o bardzo wysokiej, nieosiągalnej wcześniej wytrzymałości na rozciąganie i dużej odporności chemicznej.

Tradycyjne naprawy i wzmocnienia budynków polegały na wymianie lub uzupełnieniu zniszczonych elementów lub na powiększaniu przekrojów w celu zapewnienia większej nośności. Tego typu działania są niekorzystne w odniesieniu do obiektów historycznych i zabytkowych. Natomiast takie cechy nowych materiałów kompozytowych jak lekkość, dobra przyczepność do podłoża i doskonałe właściwości mechaniczne sprawiają, że mogą być one szczególnie przydatne do napraw konstrukcji obiektów historycznych. Poza tym materiały kompozytowe w niewielkim stopniu ingerują w cenną substancję zabytkową i zwykle możliwy jest ich demontaż. Czyni to ich stosowanie zgodnym z aktualną doktryną konserwatorską. Początkowo stosowano systemy FRP (Fibre Reinforced Polymer) z długimi włóknami o wysokiej wytrzymałosci osadzonymi w matrycy z żywic syntetycznych. Od kilkunastu lat dostępne są również wyroby FRCM (Fibre Reinforced Cementitious Matrix) z matrycą z modyfikowanej zaprawy cementowej. Zastosowanie matrycy nieorganicznej oznacza pokonanie ograniczeń powodowanych przez żywice epoksydowe stosowane w systemach FRP. Jest to możliwość montażu systemów FRCM na wilgotnych podłożach, odporność na wysoką temperaturę, przepuszczalność pary wodnej oraz łatwość aplikacji.

Kamienne kolumny arkad na dziedzińcu Pałacu w Baranowie Sandomierskim wzmocniono opaskami z maty z włókna węglowego FRP. Wyeliminowano zastosowane wcześniej nieestetyczne stalowe obręcze. Miejsca napraw uzupełniono metodami konserwatorskimi warstwą zaprawy dopasowanej kolorem do barwy kamienia dzięki czemu stały się one całkowicie niewidoczne. Murowane ceglane filary w kamienicach krakowskich wzmacniano wklejając poprzecznie kompozytowe pręty zbrojeniowe.

Tradycyjnie wzmacnianie sklepień dodatkową warstwy betonu zbrojonego lub ich odciążanie za pomocą dodatkowych stalowo-żelbetowych stropów skutkuje zwiększeniem obciążeń ścian i fundamentów oraz poważnie ingeruje w historyczną strukturę. Nośność sklepienia można zwiększyć naklejając siatkę kompozytową na dolnej i górnej powierzchni w rejonach, gdzie występuje rozciąganie. Metoda ta zastosowana w Pałacu Królewskim w krakowskim Łobzowie i w budynku szkoły w Gorlicach okazała się skuteczna.

Konstrukcje murowe budynków wymagają stężeń. Tradycyjne drewniane stropy belkowe nie są wystarczające. Podczas remontów dodatkowe wieńce mogą być wykonane ze stalowych kątowników mocowanych wewnątrz do belek i ścian, a gdy pozwalają na to względy konserwatorskie wieńce z pasów siatki kompozytowej naklejane są na zewnętrznej stronie murów. Mogą one zostać ukryte w grubości tynku.

Konstrukcje sklepień i ściany historycznych budynków sakralnych ulegają uszkodzeniom na skutek niedostatecznej sztywności elementów, których zadaniem jest równoważenie siłrozporu od sklepień. W budynku synagogi w Słonimiu na Białorusi zaprojektowano nad sklepieniem system cięgnowy złożony ze stalowych ściągów spinających ściany zewnętrzne uzupełniony klejonymi do ścian

taśmami FRP. Podobnie materiały kompozytowe wykorzystano do wzmocnień kopułw Krasiczynie, Lądzie i Gostyniu koło Poznania.

Elewacje kamienne ulegają uszkodzeniom korozyjnym, które wymagają konstrukcyjnych zabezpieczeń. Kamienne balkony budynku urzędu miasta w Warszawie planowano naprawić wykonując ich demontaż i ponownie osadzić na nowej konstrukcji wsporczej wykonanej z kształtowników stalowych. Zrealizowano projekt zamienny z wykorzystaniem taśm z włókna węglowego i stalowych spiralnych prętów kotwiących.

Podejmowane są próby wzmacniania za pomocą materiałów kompozytowych drewnianych belek. Skuteczność takich napraw zależy w dużym stopniu od konserwatorskich możliwości uzupełnienia przekrojów dodatkowymi elementami. Badania zginania zabytkowych belek były prowadzone tylko do osiągnięcia założonych dopuszczalnych ugięć belek, a nie do ich zniszczenia. Nośność po wzmocnieniu wzrastała o około 5%. Wyniki uzyskiwane na porównawczych belkach nowych wykazały znacznie większe wartości ugięć w momencie zniszczenia wzmocnionych belek w porównaniu z belkami bez wzmocnień. Świadczy to o istotnym wpływie wzmocnień kompozytowych na bezpieczeństwo drewnianej konstrukcji.

Przykłady zastosowań systemów kompozytowych w budynkach historycznych potwierdzają ich zgodność z obowiązującą doktryną konserwatorską i skuteczność wykonanych napraw. Należy przewidywać, że oprócz opisanych metod również wstępne naprężanie kompozytów, które okazało się skuteczne w przypadku żelbetu znajdzie zastosowanie w dziedzinie konstrukcyjnych wzmocnień budynków historycznych.

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