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Strengthening of reinforced concrete structures by composite materials taking into consideration the carbonization of concrete

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Abstract. One of the main causes for deterioration of reinforced concrete structures in modern construction is corrosion of reinforcement. Corrosion leads to decrease of adhesion between reinforcement and concrete, formation of cracks and destruction of the protective layer of concrete. All this reduces the load-bearing capacity of reinforced concrete structures. The structures of sludge reservoirs exposed to carbon dioxide were used as an object of the study. The characteristic defects and damages revealed by visual inspection were described. The verification calculation of the considered construction depending on the pH of the medium was performed on the basis of the results of technical inspection and study. The degree of carbon dioxide impact on the considered structures was determined by the phenolphthalein test method, which is based on the color change of acid-base indicator solution on the surface of concrete and reinforced concrete depending on the pH value of its medium. The phenolphthalein test revealed that pH of the medium is less than 8 for the depth more than the thickness of the concrete protective layer. A verification calculation of the considered structure was performed on the basis of the technical inspection results and the conducted research. According to the calculation results, a variant of beam reconstruction and strengthening using external reinforcement based on carbon fibers FibARM 230/150 was proposed. The reconstruction was carried out with account of the carbonized concrete layer.

Keywords: corrosion of reinforcement, technical inspection, calculations of building structures, composite materials, strengthening of building structures

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Усиление железобетонных конструкций композитными материалами с учетом карбонизации бетона

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Аннотация. В современном строительстве одной из основных причин износа железобетонных конструкций является коррозия арматуры. Из-за нее снижается сцепление арматуры с бетоном, образуются трещины и разрушается защитный слой бетона, вследствие чего снижается несущая способность железобетонных конструкций. Объектами исследования выступили конструкции шламбассейна, которые подвергались воздействию углекислого газа. Описаны характерные дефекты и повреждения, выявленные при визуальном осмотре. Степень воздействия углекислого газа на рассматриваемые конструкции определялась методом фенолфталеиновой пробы, который основан на изменении окраски раствора кислотно-основного индикатора на поверхности бетона и железобетона в зависимости от показателя pH его среды. При проведении фенолфталеиновой пробы выявлено, что pH среды менее 8 на глубине более чем толщина защитного слоя бетона. Выполнен поверочный расчет рассматриваемой конструкции, по результатам которого представлен вариант восстановления и усиления балки с использованием внешнего армирования на основе углеродных волокон FibARM 230/150. Восстановление проводилось с учетом слоя карбонизированного бетона.

Ключевые слова: коррозия арматуры, техническое обследование, расчеты строительных конструкций, композитные материалы, усиление строительных конструкций

1. Introduction

In modern construction, one of the main causes of failure of reinforced concrete structures is corrosion of steel rebars. Due to corrosion, the adhesion between reinforcement and concrete decreases, cracks are formed, and the concrete protective layer is destroyed, which reduces the load-bearing capacity of reinforced concrete structures. One of the main reasons for corrosion of reinforcement is carbonization [1–5]. Carbonation is the change that occurs in portland cement concrete when carbon dioxide CO_2 affects it. Due to the destruction of the concrete due to corrosion of the reinforcement, the structure of the concrete must be restored first, and in the future it may be necessary to strengthen these structures. In this case, one of the most effective ways of strengthening is the use of composite materials for this purpose.

One of the earliest composite materials is single-directional fiberglass, made from continuous glass fibers that are bonded with a polymer matrix. This material was developed by engineer A.K. Burov at the end of the 30s. In the following years this direction was widely developed by the Russian scientists and was connected with the use of composite materials in different areas of science and technique also when repairing and strengthening of building structures [6–7].

At present, composites on the basis of fibers, which are subdivided into carbon, aramid, and fiberglass, are used for repairing and strengthening of building structures. In turn, fibers are made from microfibers, which are further monolithed in a curing polymer (epoxy and polyacrynitrile resins).

The first experimental studies related to the use of composite materials for repair and reinforcement of reinforced concrete structures were conducted in Germany in 1979. At about the same time composite materials were also used in Japan to reinforce columns by the method of forming clips.

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Composite materials have found wide application in bridge and large-span structures, where they are used as the basic material for reconstruction. This was facilitated by some advantages that are characteristic of composite materials, namely: high corrosion resistance, low weight, high strength (4000 MPa) and tensile modulus of elasticity (245 GPa), the ability to take any required shape depending on the shape of the reinforced structure [8–9].

The world experience of application of composite materials is successful since during service time of reinforced elements there have not been revealed any reaching of limit states of the first and second categories in the external reinforcement. The considered advantages of the applied material allow its use as a material to strengthen the structures of the sludge reservoir.

2. Methods

To conduct the research, we studied silt reservoir structures, which were exposed to carbon dioxide CO_2, resulting in the formation of calcite $CaCO_3$ in the body of the structure. This indicates the occurrence of the reaction of carbonization in the body of the reinforced concrete structure (Figure 1) [10–12]:

– destruction of the protective layer of concrete beams with bare and corrosive damage to the power reinforcement in the lower zone and support units;

– failure of the adhesion of the working reinforcement to the concrete due to corrosion of the reinforcement and destruction of the concrete;

– longitudinal cracks in the concrete formed because of reinforcement's corrosion.

Figure 1. Corrosion of reinforcing bars in a beam

The method of phenolphthalein testing is based on the change in color of the acid-base indicator's solution on the surface of concrete and reinforced concrete depending on the pH value of its medium [13].

The value of pH of non-carbonized concrete is within the range of 11.5–12.5. At this value, the medium is highly alkaline, which helps protecting the steel reinforcement from corrosion inside the body of the concrete. Carbonation leads to the saturation of concrete pores with carbon dioxide from the air, which causes the neutralization of the main component – “free” calcium hydroxide, according to the reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O.$$

Phenolphthalein solution is applied to a fresh splinter (saw cut) of concrete made on the structure under investigation. In the range of pH values from 8–10 the color of indicator solution changes from a colorless to crimson (pink-purple), which helps to identify centers of carbonization and allows to determine their actual depth (Figure 2). The absence of coloring of the indicator solution on the surface of the concrete, without visible signs of its corrosion damage during visual control, indicates the absence or a small amount of carbonization [14–15].

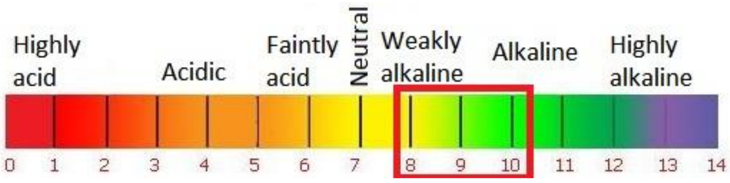

Figure 2. The pH range of color change in phenolphthalein solution

The phenolphthalein test revealed that the pH of the medium was less than 8, to a depth greater than the thickness of the protective layer of concrete (Figure 3). It was used 1% phenolphthalein solution in ethanol to conduct the phenolphthalein assay.

Figure 3. Absence of visible signs of concrete carbonization from the results of phenolphthalein test

Then a verification calculation of the structure was performed. A plan for restoration of the damaged structure was made based on the results of this calculation.

3. Results and analysis

The paper proposes the calculation of strengthening of a reinforced concrete beam by canvas based on carbon fibers FibArmTape 230/150. The purpose of this calculation is to determine the bearing capacity of the beam to evaluate its ability for further operation after restoration works.

The characteristics of FibArmTape 230/150 composite material are shown in Table.

Characteristics of FibArm Tape 230/150

Type of composite material	Estimated thickness, mm	Tensile strength, MPa	Tensile modulus of elasticity, GPa	Square of a monolayer, mm^2
FibArmTape 230/150	0.128	4000	245	19.2

The beam is made of B15 class concrete. The maximum dimensions of the beam are 600×200 mm. The beam is subjected to loads from its own weight, roof slabs, as well as the weight of the roof covering pie – 106.65 kN/m. Figure 4 shows a diagram of bending moments in the beam.

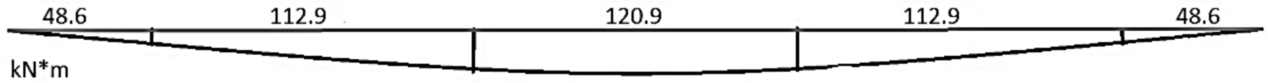

Figure 4. Diagram of bending moments in the beam

The estimated value of tensile strength:

$$R_f = \frac{\gamma_{f1}\gamma_{f2}R_{f,n}}{\gamma_f} = \frac{0,9 \cdot 0,9 \cdot 4000}{1.2} = 2700 \text{ MPa},$$

where $R_{f,n}$ – the normative value of the tensile strength of the composite material, MPa; γ_f – the coefficient of reliability for the composite material; γ_{f1} – the coefficient of the operating conditions, depending on the type of composite material and operating conditions of the structure; γ_{f2} – the coefficient of operating conditions of the composite material, considering the adhesion of the composite material with the concrete.

When calculating a strengthened structure considering the existing steel reinforcement, the following condition should be fulfilled:

$$R_f \le (\varepsilon_{s2} - \varepsilon_s^0)E_f,$$

where ε_{s2} – a coefficient equal to 0.015; ε_s^0 – the initial relative deformation of steel reinforcement before reinforcing of the structure; E_f – the estimated value of modulus elasticity of composite material.

$R_f = 2700 \le 1225$, the condition is not satisfied, so we take $R_f = 1225$ MPa.

$$\varepsilon_s^0 = \frac{12.09}{0.209 \cdot 71530} 27 = 0.02.$$

The calculation of strength in cross-sections of bendable elements strengthened by external reinforcement from composite materials, should be carried out from the condition:

$$M \le M_{\text{ult}};$$

$$M_{\text{ult}} = R_b bx(h_0 - 0,5x) + R_{sc}A_s'(h_0 - a') + R_f A_f a;$$

$$M = 120.9 \text{ kN} \cdot \text{m} \le M_{\text{ult}} = 131.1 \text{ kN} \cdot \text{m}.$$

The condition is fulfilled, so we take 1 layer of tape on the bottom edge of the beam. Also, the calculation of the bending element by inclined sections on the action of transverse forces (Figure 5) was carried out. The calculation was carried out basing on the following condition:

$$Q \leq Q_b + Q_{sw} + Q_{fw},$$

where Q_b – the transverse force taken up by the concrete in the inclined cross-section; Q_{sw} – the transverse force taken by the steel transverse reinforcement installed in the sloping cross-section with a step of s_w; Q_{fw} – transverse force taken by the composite transverse reinforcement in the sloping section and determined by the formula

$$Q_{sw} = \psi_f \left(\frac{A_{fw} R_{fw} \sin \alpha \, C_{fw}}{s_f} \right).$$

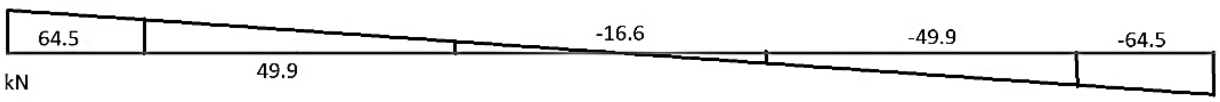

Figure 5. Diagram of transverse forces

By the results of calculations carried out in the software package SCAD in accordance with the procedure BR 63.13330.2018, it was determined that Q_h = 87.21 kN, Q_{sw} = 186.5 kN, Q_{fw} = 38.97 kN. Hence, Q = 64.5 ≤ 87.21 + 186.35 + 38.97 = 312.53 kN.

According to the calculation, the external transverse reinforcement is not required, therefore, take structurally 3 external clamps of 75 mm wide at three sides of the beam support, at the distance of L/8 and L/4, to a height of not bringing 20 mm to the top edge of the beam.

4. Conclusion

As a result of the technical inspection and verification calculations, a version of the beams strengthening was made. The scheme of beams restoration and reinforcement is shown in Figure 6.

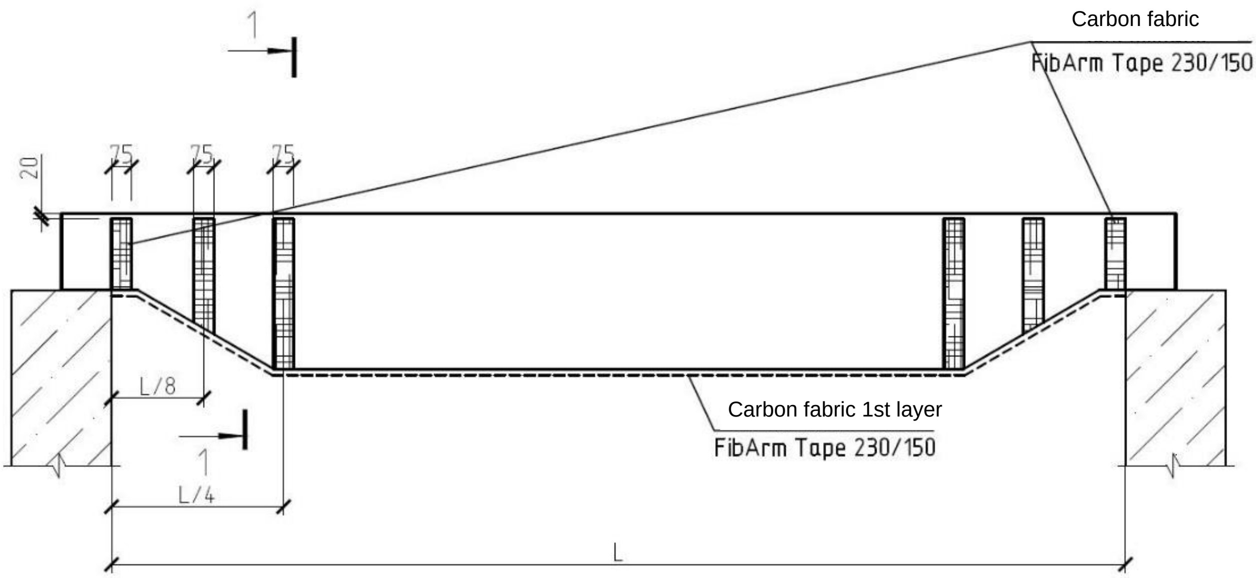

Figure 6. Diagram of beam strengthening using composite materials

The considered approach to the restoration with further strengthening by the composite materials allows to increase the lifetime of the structure as well as to provide the required bearing capacity of the structure for the purpose of further safe operation of the object.

Thus, when the destruction of concrete protective layer and corrosion of reinforcement is detected, the most probable reason is carbonization of concrete with increased impact of CO_2 on the operated structure.

The use of composite materials for construction and restoration of concrete structures makes it possible to minimize the probability of their destruction in the process of their operation.

On the basis of the test results, repairs and restoration of the damaged areas of the concrete were carried out. Removal of the carbonized layer of concrete was performed using a mechanized method. If the depth of carbonation exceeds the thickness of the protective layer of concrete, then the damaged concrete is removed behind the reinforcement.

Scrubbing of the reinforcing bars surface from products of corrosion was carried out using manual metal brushes with further treatment of the bars using corrosion converter. Docker Nittron's neutral tannite-based corrosion inhibitor was used because it does not cause damage to concrete or cement repair mixtures with acidic media, unlike acidic corrosion inhibitors.

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