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THE REASONS OF DESTRUCTION OF REINFORCED CONCRETE BEAMS WITH CARBON FIBER REINFORCED POLYMER (CFRP). MEASURES FOR PREVENTION SUCH DESTRUCTION

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The article describes reasons of destruction of reinforcement systems for concrete beams with carbon fiber reinforced polymer (CFRP). Given the calculation of parameters for prevention of repeated repair of structures. Using these strategies, it will be possible to eliminate all errors of external reinforcement by composite materials and significantly improve the operational state of reinforced concrete structures.
Keywords: carbon fiber reinforced polymer, strengthening, reinforced concrete, destruction.

Introduction. An effective way of increasing the bearing capacity of reinforced concrete bridge beams is the use of modern systems strengthening with composite materials (CFRP). Strengthening of reinforced concrete structures by external reinforcement prestressing reinforcement beams used as construction method since 1950. Currently, the preliminary tension of the reinforcing beams is widely used for strengthening of reinforced concrete structures in the United States, China, Europe, Russia and other countries.

Experience indicates that a lot of repaired and strengthened structures have failures during the first five years of operation. The success of the application of composite materials depends largely on the quality of substrate preparation for label laminates and canvas.

Preparation for repair and subsequent intensification should include measures for blocking reinforcement corrosion, which usually develop at the first signs of destruction. Without proper preparation re-repair will be inevitable.

The main types of destruction of reinforced concrete structures reinforced with carbon fiber reinforced polymer (CFRP).

The main reasons of destruction of reinforced concrete beams with carbon fiber reinforced polymer (CFRP) can be divided into two groups:

- capacity of the reinforced structure is retained until the beginning of the destruction of concrete of the compressed zone or the destruction of the stretched composite material;
- destruction of the construction comes earlier because of the detachment of composite material from concrete.

Total destruction of the structure may come in the following cases:

- plastic destruction of the reinforcement of the stretched zone when stresses in the rod armature of the physical (conditional) yield point with further destruction of the concrete in compressed zone. If the structure is reinforced with a high-strength wire with a small relative elongation at break (about 4%), then simultaneously with the rupture of the wire, the concrete of the compressed zone is crushed;
- brittle destruction of concrete in the compressed zone in elements with an excessive content of stretched steel reinforcement and a stretched composite material. The use of external reinforcement in this case is ineffective;
- plastic destruction of the reinforcement of the stretched zone with a small percentage of reinforcement by composite materials, which primarily leads to their rupture and redistribution of the load on the internal steel reinforcement, which is why its destruction begins.

Local destruction of the reinforced concrete reinforced by external reinforcement can occur due to loss of adhesion between concrete and composite material, and also due to the destruction of contacts of the layers (adhesion destruction). Disturbance of the adhesion between the concrete surface and the composite material under the influence of normal and tangential stresses leads to local destruction of the structure, which must be taken into consideration during of determination bearing capacity with regard to external reinforcement. In most cases, this kind of failure occurs at the cracked portion. When it spreads to other areas, the external composite material loses its ability to absorb loads and it detaches from the concrete. In the absence of the possibility of redistribution of stresses from the external reinforcement from the composite material to internal steel, the detachment can be a fragile nature and occur suddenly.

In general, as a result of repair and reinforcement of the reinforced concrete bridge beams by external reinforcement with composite materials (CFRP), its cross-section is a layered structure (Figure 1). Destruction in this case is possible on the following five layers and the surfaces of their section:

- cohesive destruction — destruction in old concrete directly at the bonded surface or near the internal stretched reinforcement. During the repair work this type of destruction also applies to the repair composition used. The normative tensile strength of concrete or repair composition should be 1.5-3.0 MPa;
- adhesion destruction — destruction on the boundary between old concrete and repair composition. To prevent this type of destruction, it is necessary to use a system repair composition that has high adhesion with deformation properties close to the deformation properties of existing concrete, which will ensure their joint operation. Adhesion of the adhesive composition to concrete should be 2.0-2.5 MPa;
- destruction in the adhesive composition. The tensile strength of the systemic adhesive is usually higher than concrete, and therefore the destruction takes place in concrete. Destruction on this surface can occur only at high temperature (above the glass transition temperature) or at very high tensile strength of concrete.
- destruction on the contact between concrete and the adhesive composition or between adhesive composition and the CMB strip. This type of destruction is possible only if the concrete surface is poorly prepared during the bonding of the strip of composite material. In all cases, the adhesion between the layers should be at least 2.0-2.5 MPa;
- **destruction of composite material.** This kind of destruction is possible only with poor-quality surface treatment, with improperly designed amplification and when the loads acting on the structure exceed the maximum values adopted in the project.

Depending on the initial point of the process of destruction, can be distinguished 4 types of destruction (Figure 2).

Type 1. Destruction begins in the cracked anchoring zone. The composite material can peel off in this zone as a result of crushing of concrete under the action of shear stresses on the contact of the layers.

Type 2. The peeling of the composite occurs as a result of the formation of flexural cracks from the action of the external load. Cracks in the concrete, initially normal to the longitudinal axis of the element, may further extend horizontally. The strip of composite material will peel off in the central part of the structure, away from the anchoring zones.

Type 3. Detachment of the composite as a result of the formation of inclined cracks as a result of the combined action of normal and tangential stresses, and which can be dominant in the peeling of the strip of composite material. However, in structures with sufficient internal and external transverse reinforcement, the formation of such cracks is unlikely and detachment of the composite material is possible only with insufficient lateral reinforcement.

Type 4. The detachment of composite material can be caused by uneven surface of concrete. The unevenness and roughness of the concrete surface are stress concentrators and as a result can cause the initial local loss of adhesion of the CMB strip to concrete, which can spread further and cause detachment.

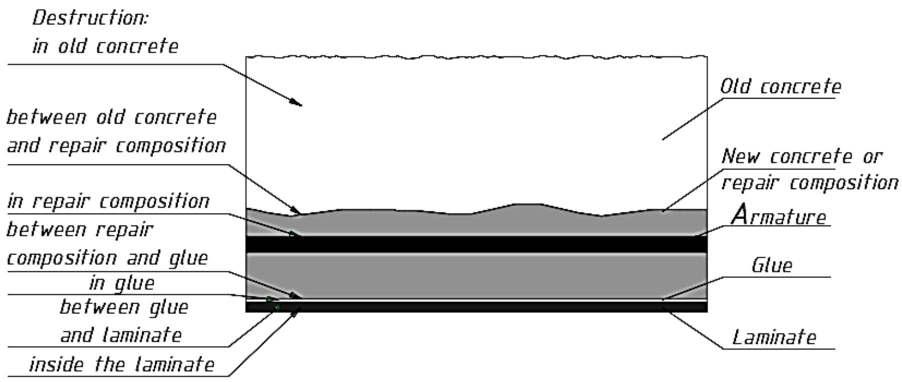

Fig. 1. Possible destruction surfaces of reinforced (repairable) structure

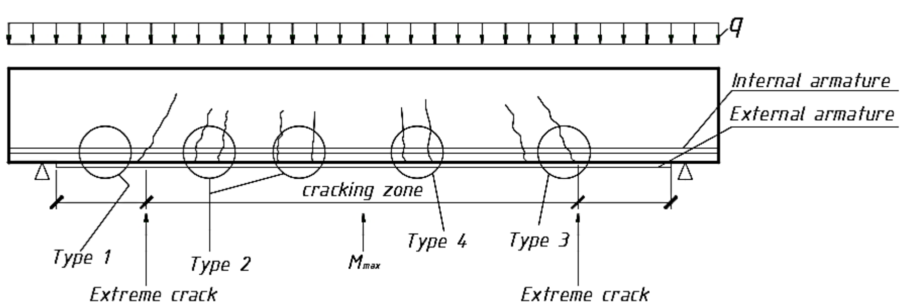

Fig. 2. Types of destruction of a reinforced concrete structure reinforced with a composite strip

The most typical places of occurrence of destruction are:

- abutment of secondary beam to the main beam;
- modification in geometric dimensions of reinforced beams cross section;
- breaking of a part of the stretched reinforcement rods;
- modification composite material width and thickness;
- breakage of the strip of composite material before the support;
- application of concentrated force.

In all these places there are jumps of tangential stresses are observed on the boundary between concrete and the strip of composite material, which leads to the detachment of the latter, and, consequently, to the destruction of the structure. These places need additional anchoring in the length of the reinforced structure.

Recommendations for the calculation of reinforced concrete beams with carbon fiber reinforced polymer (CFRP).

The distribution of normal and tangential stresses at the end of the strip composite material glued to the concrete is shown in Figure 3.

The maximum stresses are valid at the end of the carbon fiber reinforced polymer strip (up to 150-200 mm), while the tangential stresses in absolute magnitude are several times higher than the normal ones.

Before calculating the reinforcement of reinforced concrete beams for the effect of bending moment, it is required to determine the maximum adhesion force that can be transferred from concrete to the composite material, and also to estimate shear stresses and normal stresses at the interface between concrete and composite material.

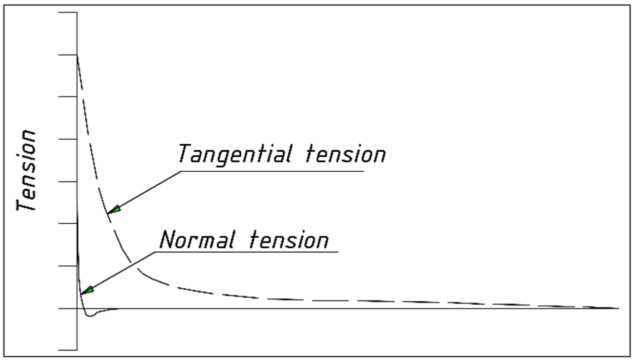

Fig. 3. Distribution of normal and tangential stresses at the end of the strip of composite material

During determining the adhesion strength, the limiting value of the force transferred to the composite system before detachment depends of the length of the clutch section. The optimal length of the clutch section l_e is determining as the length, at the excess of which there is no increase in the force transferred from the concrete to the composite.

The optimal length of the section of the composite material with the clutch l_e, is determined by the formula:

$$l_e = \sqrt{\frac{E_c \cdot t_c}{2 \cdot R_{bt}}}, \text{ mm} \qquad (1)$$

E_c – modulus of elasticity of the composite material; t_c – thickness of composite material; R_{bt} – concrete tensile strength.

Specific adhesion of the composite material to concrete, N_c, is determined by the formula:

$$N_c = 0,03 \cdot k_b \cdot \sqrt{R_{bn}} \cdot R_{bt} \qquad (2)$$

R_{bn} – the normative strength of concrete for compression; k_b – is the geometric coefficient depending on the width of the reinforced structure, b, and on the width of the composite material, b_c.

The coefficient k_b is determined in the following way:

$$k_b = \sqrt{\frac{2 - \frac{b_c}{b}}{1 + \frac{b_c}{400}}} \qquad (3)$$

$\frac{b_c}{b} \geq 0.33$ (if $\frac{b_c}{b} \geq 0.33$, accepted the value of k_b corresponding to $\frac{b_c}{b} \geq 0.33$).

In order to avoid delamination of the end sections of composite materials, their strength σ_{sk} should be determined by the formula:

$$\sigma_{sk} = \frac{1}{\gamma_{cd \cdot \sqrt{\gamma_c}}} \cdot \sqrt{\frac{2 \cdot E_c \cdot N_c}{n_c \cdot t_c}} \qquad (4)$$

γ_{cd} – is the reliability factor for the composite material, which is 1.2 for certified components and the composite material, and 1.5 for certified components of the composite material; γ_c – coefficient of reliability for concrete.

When using special anchor devices (transverse reinforcement rods made of composites, U-shaped wrapping with sheet composite material, etc.), the maximum strength of the composite material must be determined directly using specially selected experimental tests for this case.

To prevent detachment of the composite material in the middle section of the reinforced structure, their strength should be determined by the formula:

$$\sigma_{sk1} = \frac{k_{sk}}{\gamma_{cd \cdot \sqrt{\gamma_c}}} \cdot \sqrt{\frac{2 \cdot E_c \cdot N_c}{n_c \cdot t_c}} \qquad (5)$$

k_{cr} – is accepted the value 3.0.

The corresponding value of the calculated strain, ε_c, in the composite system should be determined by the formula:

$$\varepsilon_c = \frac{\sigma_{sk1}}{E_c} \qquad (6)$$

During the operation of reinforced concrete beams reinforced with composite material, the shear stress at the interface between the adhesive and concrete, $\tau_{b,e}$, should be less than the calculated bond strength between the composite material and concrete, f_{bd}, and is determined by the formula:

$$\tau_{b,e} \leq f_{bd} \qquad (7)$$

The shear stress, $\tau_{b,e}$, should be determined by the formula:

$$\tau_{b,e} = k_{id} \cdot \tau_m \qquad (8)$$

k_{id} – coefficient (≥ 1) which consider the shear stress and normal stresses near the end sections of the anchoring, determined by the formula:

$$k_{id} = \left(k_{\sigma}^{1.5} + 1.15k_{\tau}^{1.5}\right)^{2/3} \quad (9)$$

The coefficients k_{σ} and k_{τ} should be determined by the formula:

$$k_{\sigma} = k_{\tau} \cdot \beta \cdot t_f \quad (10)$$

$$k_{\tau} = 1 + \alpha \cdot a \cdot \frac{M_{(z-a)}}{Q_{(z-a)\cdot a}} \quad (11)$$

$M_{(z-a)}$ – is the bending moment acting on the end section of the reinforced concrete structure (Figure 4); $Q_{(z-a)}$ – is the transverse force acting on the end section of the reinforced concrete structure.

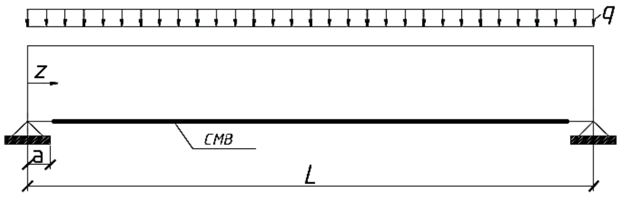

Fig. 4. Scheme of geometric parameters of the reinforced concrete structure:
a – the value of the attachment of the CMB to the center of the support, mm; z – current coordinate, q – uniformly distributed load

he coefficients α and β are two elastic parameters, which should be determined by the formulas:

$$\alpha = \sqrt{\frac{K_1}{E_c \cdot t_c}} \quad (12)$$

$$\beta = \left(\frac{b_c \cdot 2.3 \cdot K_1}{4 \cdot E_c \cdot I_c}\right)^{1/4} \quad (13)$$

E_c – modulus of elasticity of the composite material; t_c – thickness of the composite material; b_c – width of the composite material; I_c – moment of inertia of the composite material; K_1 – a parameter that should be determined by the formula:

$$K_1 = \frac{1}{t_a / G_a + t_b / G_b} \quad (14)$$

G_a – shear modulus of adhesive composition; G_b – modulus of shear of concrete, t_a – thickness of adhesive composition, t_b – reduced thickness of concrete (the standard values of t_b are 20-30 mm).

The average shear stress τ_m, in accordance with Zhuravsky's theory, should be determined by the formula:

$$\tau_m = \frac{Q_{(z-a)} \cdot t_c \cdot (h - x_e)}{I / \beta} \quad (15)$$

x_e – distance from the end of the compression fiber to the neutral axis;

I – moment of inertia of the reduced section; $\beta = E_c / E_b$ – coefficient of ratio of modulus of elasticity of composite material and concrete.

If is provided a U-shaped cage end anchorage, the action of normal stresses can be neglected, and the coefficient k_{σ} in (10) is assumed to be zero.

The calculated bond strength, f_{bd}, is a function of the tensile strength of concrete, R_{btn}, and is determined by the formula:

$$f_{bd} = k_b \cdot \frac{R_{btn}}{\gamma_b} \quad (16)$$

γ_b – coefficient, taken equal to 1 for emergency combinations of loads, 1.2 for steady-state combinations of loads.

For single-span reinforced concrete beams, the reinforcement of the composite material should be wound at least at a distance le after the point along the span corresponding to the moment of crack formation M_{cr}. For multilayer strengthening of materials, the end points of the layers must be moved apart, forming a wedge-shaped surface.

For multi-span beams, the single-layer coating of the composite system must be completed at a distance of at least 150 mm from the point of inflection (the zero point point of the resulting design loads). For multilayer coatings of composite materials, the outer layer must be finished at a distance of at least 150 mm from the inflection point.

These recommendations apply to areas with positive and negative moments.

Conclusions. In the article there were described different reasons of destruction of reinforcement systems for concrete beams with carbon fiber reinforced polymer. Band of composite material, which are glued to the stretched edge of reinforced concrete elements, increase their resistance to bending and increase the flexural rigidity of the beams, which leads to a reduction in deflections.

The effectiveness of reinforcement with CFRP by the gluing method depends on the observance of three important conditions:

– glued surfaces must be in a clean, well-prepared and flat condition;

– the adhesive should have at least the same tensile and shear strength as concrete and be usable in the environment prevailing for the given object;

– to prevent brittle fracture of band and its detachment from the reinforced structure, they must be thin and long.

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ПРИЧИНИ РУЙНУВАННЯ ПІДСИЛЕННЯ ЗАЛІЗОБЕТОННИХ БАЛОК МОСТІВ КОМПОЗИЦІЙНИМИ МАТЕРІАЛАМИ (CFRP). ЗАХОДИ ЩОДО ЗАПОБІГАННЯ ТАКИХ РУЙНУВАНЬ

Анотація
У статті описані причини руйнування систем підсилення залізобетонних балок композиційними матеріалами з полімерною матрицею (CFRP). Наведено розрахунок параметрів для запобігання повторного ремонту конструкцій. Керуючись цими рекомендаціями, можна усунути всі погрішності зовнішнього армування композиційними матеріалами і значно підвищити експлуатаційний стан залізобетонних споруд.
Ключові слова: композиційний матеріал, укріплення, залізобетон, руйнування.

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ПРИЧИНЫ РАЗРУШЕНИЯ УСИЛЕННЫХ ЖЕЛЕЗОБЕТОННЫХ БАЛОК МОСТОВ КОМПОЗИЦИОННЫМИ МАТЕРИАЛАМИ (CFRP). МЕРЫ ПО ПРЕДОТВРАЩЕНИЮ ТАКИХ РАЗРУШЕНИЙ

Аннотация
В статье описаны причины разрушения систем усиления железобетонных балок композиционными материалами с полимерной матрицей (CFRP). Приведен расчет параметров для предотвращения повторного ремонта конструкций. Руководствуясь данными рекомендациями, можно устранить все погрешности внешнего армирования композиционными материалами и значительно повысить эксплуатационное состояние железобетонных сооружений.
Ключевые слова: композиционный материал, укрепление, железобетон, разрушение.