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Strengthening and restoration of damaged reinforced concrete structures with composite plastics

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Abstract. This paper considers directions to devise methods for restoring the operational suitability of reinforced concrete structures. Mistakes of designers and non-compliance with the concreting technology of monolithic reinforced concrete structures lead to the formation of cracks and deflections of unacceptable size in reinforced concrete beams and floor slabs, as well as to insufficient strength of the elements. Such structures require not only an increase in bearing capacity but also the restoration of the operational suitability of damaged structures. A technique for restoring the serviceability of bendable reinforced concrete structures with increased deflections and excessive crack opening is proposed. To restore bendable reinforced concrete structures, surface reinforcement with pre-stressed fiber-reinforced plastics is suggested, which is ensured by the creation of a building lift in the damaged elements. Unlike conventional reinforcement methods, surface reinforcement techniques are characterized by high gain efficiency, corrosion resistance, low labor intensity, and short terms of work; they ensure strength increase and provide for economic feasibility. This study's results established that the use of fiber-reinforced plastics not only increases the bearing capacity of reinforced concrete structures but also helps reduce the width of the cracks formed. Thus, it is possible to avoid an increase in the cross-section of structures and reduce the time of operations, which could lead to additional costs.

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1. Introduction

For more than 15 years, the use of fiber-reinforced tapes to strengthen reinforced concrete structures has been investigated worldwide but the relevance of studies is not lost since examining them requires a deeper understanding of the work of composite materials. Fiber-reinforced plastics are composite materials consisting of a plastic matrix and high-strength reinforcing fibers, supplied in the form of ribbons (lamellas), fabrics, or meshes [1–3]. Epoxy, phenolic, polyester, vinyl ester, or other organic resins are used as plastics. Reinforcing fibers are made, by using nanotechnology, from carbon, basalt, aramid, or glass [4–6]. The composite material is found in the form of reinforcing bars and tapes. During the entire time of studying the work of the material, researchers apply all types of composite materials to conduct tests. Some types may not be economically feasible [7–8]. To identify the reasons that lead to an increase in the cost of strengthening reinforced concrete structures, samples of reinforced concrete beams were examined. Many researchers study the reinforcement of structures rather than their restoration [9–10]. Therefore, studies on the restoration of reinforced concrete structures, and reducing the width of cracks formed as a result of overstressing them are relevant [11–13]. The process of surface strengthening of reinforced concrete structures takes several hours; the reinforced structure is able to perceive additional loads in 24 hours [14–15]. These reinforcement methods are widely used for longitudinal and transverse reinforcement of the stretched zone of reinforced concrete structures, as well as the construction of reinforcing clips in compressed elements.

To accomplish the aim, the following tasks have been set:

– to determine the dynamic and static strength based on the results of laboratory tests;

– to compare the estimated and experimental strains in the beams;

– to obtain the results of a practical assessment.

2. Methods

2.1. This study's object and methods

To assess the strength and deformation characteristics of concrete, concrete cubes with a face size of 150 mm and cylinders with a diameter of 150 mm and a height of 300 mm were tested. Concrete samples were tested under axial compression at the hydraulic press ALPHA 3-3000S (Germany, Form+Test) with a phased increase in the longitudinal compressive force at a speed of 0.3 MPa/s, up to the destruction of the sample. The value of the load increase step did not exceed 5÷8 % of the destructive load. In the process of static loading of the cylinders, longitudinal and transverse strains were measured using strain gauges with a base of 50 mm, glued to the side faces of the samples, as well as the automatic deformation meter AID-4M (Russia). Loading of experimental prisms was carried out along the physical axis of the samples in stages constituting 5–10 % of the destructive load.

The strength of concrete in the cubes was in the range of 27.9–32.7 MPa, with an average of 30.4 MPa (Fig. 1). The cylindrical strength of class B25 concrete is in the range of 19.9–21.5 MPa and averages 20.6 MPa (Fig. 2, a, b). Fig. 3 shows diagrams of the longitudinal and transverse strains of concrete obtained from cylinder tests, where each line is indicated by a separate color, indicating the number of cylinders tested. The marginal longitudinal strains of concrete at compression were in the range of – (23–25)·10–4 relative units, and the transverse strains of + (7–8)·10–4 relative units.

Figure 1. Testing a concrete cube at the hydraulic press ALPHA 3-3000S.

Figure 2. Concrete cylinder:
a – test at the hydraulic press ALPHA 3-3000S; b – devices to register strains.

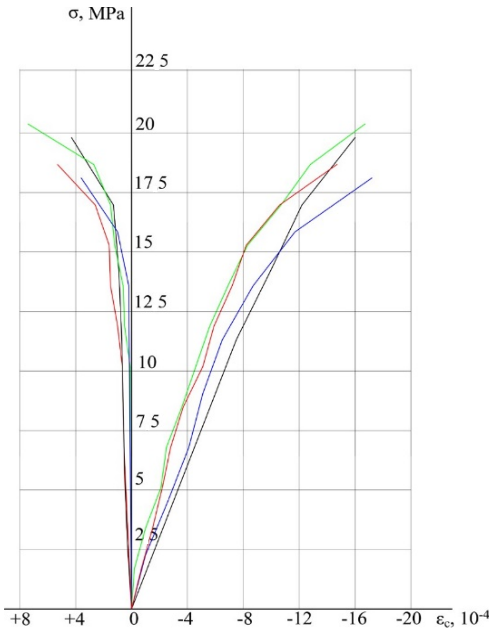

Figure 3. Diagram of longitudinal and transverse strains of concrete cylinders.

2.2. Methods of additional tests

To study the patterns of change in stiffness and crack resistance in the process of generating preliminary stress of fiber-reinforced plastics, additional tests were performed on three series of reinforced concrete beams with a cross-section of 120×200 mm and a length of 2200 mm. Experimental beams differed in the percentage of reinforcement of the stretched zone. Prototypes of the beams included three series of samples, differing in the percentage of longitudinal reinforcement. The beams from the first series had the least amount of stretched reinforcement (2 Ø 18 A500). We give the results of testing the beams from the first series. They were loaded with a hydraulic jack in stages accounting for 7–9 % of the destructive load. Comprehensive experimental studies of bendable and compressed elements reinforced with fiber-reinforced plastics included the study of the operation of normal and inclined cross-sections of bending structures [16]. The samples were subjected to surface reinforcement with carbon tapes glued to the compressed and stretched edge of the beams. The prototypes made from the B25 concrete class were tested according to the scheme of a single-span hinged beam loaded in a third of the span with equal concentrated forces. We studied the operation of normal cross-sections of bendable reinforced concrete structures on reinforced concrete beams tested according to the scheme of a single-span hinged-supported beam. The beams were loaded with two equal concentrated forces, which were generated by means of a load device for the bending bearing capacity of the beams. In the process of testing with the help of electric load cells with a base of 50 mm and the automatic deformation meter AID-4M with a division unit of 10–5 relative units, longitudinal strains of the beam were measured according to the height of the compressed concrete zone. With the help of load cells with a base of 20 mm, strains of stretched reinforcement were measured. Consequently, a pattern of the formations was recorded and the width of the crack opening was measured using a microscope with a division unit of 0.02 mm; the magnitude of the transverse load was recorded on the high-precision manometer of the hand pumping station (Fig. 4, 5). The load cells were connected to an automatic strain gauge. With their help, mechanical effects are converted into electrical signals and transmitted to the strain gauge bridge. Calibration of load cells was carried out using the readings of the strain gauge bridge and measuring the initial imbalance, as well as according to the data specified in the passport, which indicate the operating power transmission coefficient of the sensor.

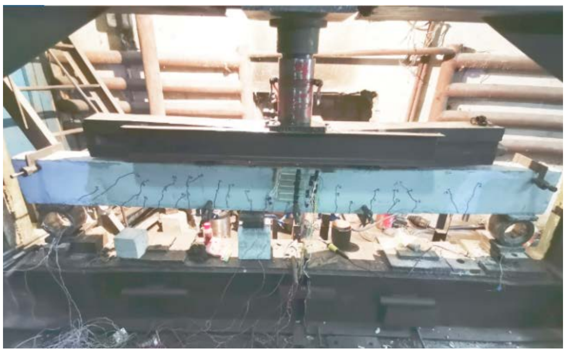

Figure 4. General view of reinforced concrete beam tests.

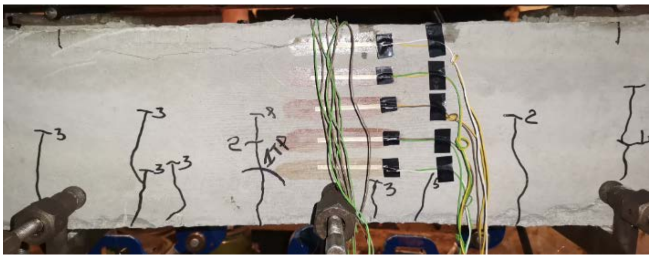

Figure 5. General view of load cells on concrete, normal cracks, and damage area of compressed concrete zone.

We loaded the samples with a transverse load in stages, constituting about 5–7 % of the destructive load, in several stages. At each stage, a load was generated that causes the predefined width of crack opening, then the load was removed and we loaded it in the next stage to a greater width of crack opening.

3. Results and Discussion

Most of the structures of civil, industrial, and bridge construction are built of reinforced concrete [17]. Given the huge investments in the construction sector, their deterioration is a serious issue for the countries that ensure their preservation [18]. Cracks that appear in reinforced concrete structures due to various factors are responsible for the integrity of a facility [19–22].

Fiber-reinforced composite materials (FRP) are increasingly being used as replacements for steel reinforcement in reinforced concrete structures. This is due to their excellent properties, such as low weight, resistance to the aggressive effects of acids, the ability to work at different temperatures, and mechanical strength [23–24]. Such advantages confirm the strength of FRP compared to alternative materials such as steel plates, and reinforcing bars [25]. FRPs, used in different forms, are effective in reinforcing damaged concrete structures [26]. Experimental studies [27] show that gluing FRPs and their full or U-shaped wrapping can significantly increase the bearing capacity of damaged reinforced concrete structures. Papers [25–26] considered options for replacing reinforcing bars with reinforcement made of composite material, which makes it impossible to restore structures in the process of its operation. The work of FRP on bending and sliding was also studied. These methods are used to provide peripheral and transverse limitations. This type of protection, in addition to strengthening the structure, can change the shape of the appearance of cracks and detachment from the concrete surface. For greater efficiency, FRP tapes are glued at a predefined angle. Study [28] shows that the use of inclined U-shaped laminates glued at the ends of the tested structures at an angle of 45° gives better results than similar gluing at a vertical angle. Gluing of external plates for structural restoration is currently studied as a method of increasing the shear strength and rigidity of reinforced concrete structures. The advantage of this method is the speed of operation, which is more economical compared to other reinforcement methods such as a concrete shell (jacket) or a complete replacement of the structure. More important is the fact that the method can be applied in the working condition of the structure [28]. The studies into the work of FRP with a reinforced concrete structure [27-29] determined at what angle of gluing a greater efficiency is achieved to strengthen the structure without restoration. Many studies have been conducted on the strength of damaged reinforced concrete structures [30] by making technological holes in a reinforced concrete structure, violating its integrity. Researchers report an experimental work [31] to increase the shear strength of reinforced concrete beams with a sprayed polymeric material reinforced with glass fiber. Methods to prevent exfoliation of composite tapes were investigated; the researchers used the anchoring method but disregarded methods of structural restoration.

The test procedure provides for the measurement of strains in the inclined and normal cross-sections under dynamic alternating loads that have not previously been examined by other authors, compared with static loads. The aim of this study is to determine the effectiveness of the use of FRP to strengthen damaged reinforced concrete structures and restore the cracks that have appeared as a result of static and dynamic loads. This will make it possible to restore the supporting structures without stopping their work without much labor and time costs.

3.1. Determining the dynamic and static strength of beams under laboratory conditions

With the magnitude of the bending moment in the beam B-18-1 equal to M = 4.42 kNm, a normal crack was formed in the zone of pure bending. Then, at the bending moment M = 13.24 kNm, the greatest width of the openings of normal cracks reached 0.13 mm, and the distance between normal cracks was in the range of 80–82 mm (Fig. 6).

Figure 6. General view of the beam B-18-1 after testing.

After generating a bending moment of M = 14.17 kNm, the vertical load was reset: that ended the first stage of our testing. Fig. 7 shows the plot of crack opening at all subsequent loading stages: each line indicates loading.

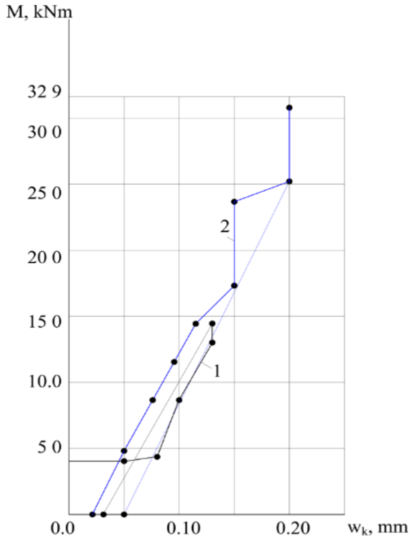

Figure 7. Evolution plot of normal cracks in the beam B-18-1.

In the second stage of the tests, the vertical load was increased to M = 19.12 kNm, and the opening width of normal cracks increased to 0.15 mm. In the next stages of loading, the load value was increased to M = 21.09 kNm, M = 25.51 kNm, and M = 26.0 kNm: no increase in the width of the normal crack opening was observed. Since the width of the crack opening has not increased, the pattern of the opening of normal cracks is given only for the first two stages of loading.

Along with the normal cracks in the zone of pure bending of the beam, there was an accelerated development of inclined cracks in the support zones. The first oblique crack was formed in the first stage of the test at a transverse force of V = 16.1 kN, and the opening width of the inclined cracks in the first stage of the tests at the transverse test V = 23.0 kN reached 0.30 mm. In the second stage of the tests at a transverse force of V = 23 kN, the opening width of the inclined cracks reached 0.40 mm, and with a transverse force of V = 30.1 kN, the opening width of inclined cracks reached 0.45 mm. In the third stage of tests at V = 33 kN, the opening width of inclined cracks reached 0.60 mm, and in the fourth stage of the test at V = 39.8 kN, the opening width of the inclined cracks reached 0.75 mm. In the fifth stage of the tests at V = 51.35 kN, the opening width of the inclined cracks reached 0.90 mm (Fig. 8). Loads are indicated under each line.

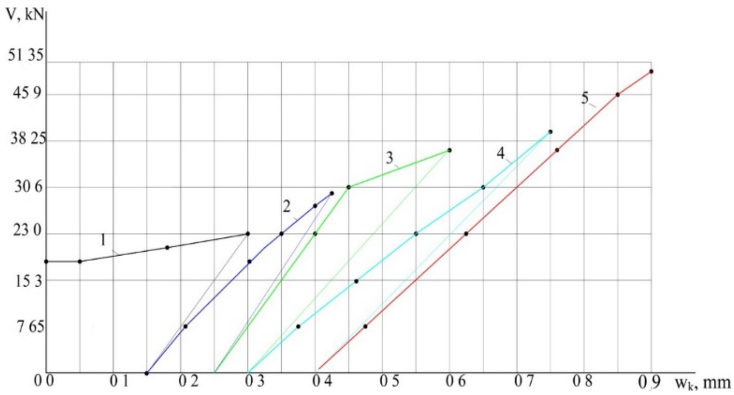

Figure 8. Evolution plot of inclined cracks un the beam B-18-1.

The beam collapsed in the zone of pure bending from the crushing of the compressed zone of concrete at a bending moment of M = 32.86 kNm (Fig. 9, a).

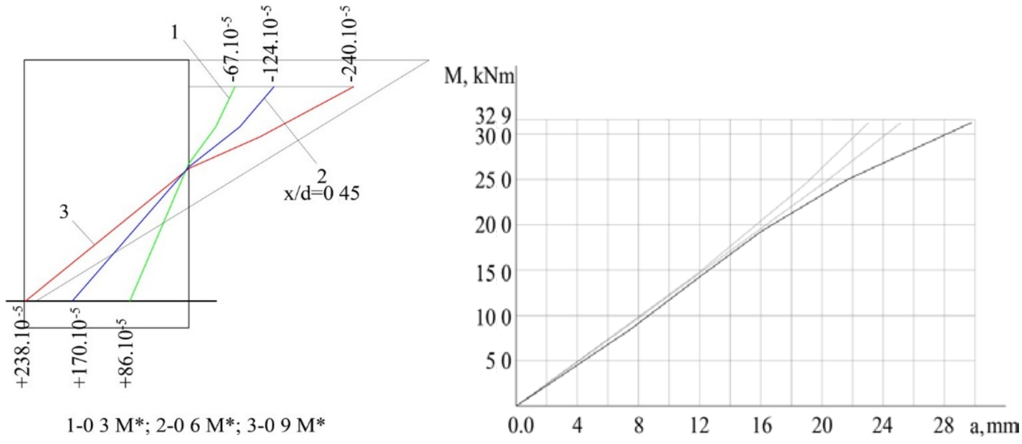

Figure 9. Diagram of beam destruction: *a* – distribution of strains across the cross-section height of the beam B-18-1; *b* – vertical deflections of the span of the beam B-18-1.

The relative value of the compressed concrete zone was ξ = d/h = 0.45 (Fig. 9, b), the magnitude of the vertical movements of the span part reached 28.6 mm, and the places of application of vertical forces were 22.8–25.1 mm, which were 1/70 and 1/63 of the span. Each line corresponds to the applied load.

3.2. Deformation calculation

The reinforcement of the beams in the stretched zone with two layers of laminate had little effect on the load of crack formation and the strength of normal cross-sections. However, the width of the crack opening was reduced by almost two times, the tensile strains in the laminate decreased by 65 %, and the vertical deflections decreased by 31 %.

Dynamic tests of the beams were carried out under cyclic alternating loading with the help of hydraulic jacks and a hydrodynamic installation with a frequency of about one hertz and an asymmetry coefficient of forces ρ = 0.1. The high amplitude of the greatest forces ensured the destruction of samples in 10÷300 cycles of loading. The empirical dependence of the destructive load $\left(M_d\right)$ on the number of cyclic loads $\left(n\right)$ is as follows:

$$\frac{M_d}{n} = 1.33 - 0.116 \lg n. \tag{1}$$

The estimated tensile resistance f_{vd} for FRP is determined from:

$$f_{yd} = \frac{f_{yk} * \gamma_{Ff}}{\gamma_f}. \tag{2}$$

The estimated tensile strains ε_f and the estimated value of the elastic modulus of deformation E_f for FRP are determined from the following formulas:

$$\varepsilon_f = \frac{\varepsilon_{uf} * \gamma_{Ff}}{\gamma_f}, \tag{3}$$

$$E_f = \frac{f_{yk}}{\varepsilon_{uf}}. \tag{4}$$

Exfoliation of the FRP can occur if the deformation in it cannot be perceived by the base.

The transverse strength of the oblique cross-section V_{cd} reinforced by FRP is defined as the sum of the cross-sectional strength without reinforcement and additional transverse force $V_{Rd,f}$, which is perceived by the FRP reinforcement:

$$V_{cd} = V_{Rd,c} + V_{Rd,xy} + V_{Rd,f}, \quad (5)$$

$$V_{Rd,f} = \frac{A_f \varepsilon_{fe} E_f \left(\sin(\alpha) + \cos(\alpha)\right)}{s_f}, \quad (6)$$

$$\varepsilon_{fe} = 0.004 \le 0.75\, \varepsilon_u, \quad (7)$$

where A_f, E_f, ε_{fe}, α, s_f are, respectively, the cross-sectional area and deformation of polymeric reinforcing meshes, their modulus of deformation, the angle of inclination, and the distance between the strips of reinforcing meshes, ε_u is the limit extensibility of polymeric reinforcing meshes.

Table 1 gives comparative indicators of the estimated and experimental strains across the height of the cross-section of the beams.

Table 1. Comparative data on estimated and experimental strains across the height of the cross-section of beams.

	The relative size of the compressed zone	ε_c, 10^{-5}	ε_s, 10^{-5}	The relative size of the compressed zone	**ε_s, 10^{-5}**
B-18-1	0.45	340	238	0.61	**223**
B-18-2	0.44	368	280	0.51	**326**

Data in Table 1 confirm the linear dependence of the relative height of the compressed zone of concrete on the percentage of longitudinal reinforcement of the stretched zone.

3.3. Results of the practical evaluation

We studied the strength of the inclined cross-sections of bendable elements reinforced with fiber-reinforced plastics during cyclic loading on similar reinforced concrete beams reinforced in the support zones with a surface sticker. The beams were tested according to the scheme of a single-span hinged supported beam loaded with two equal transverse forces separated from the supports at distances equal to l_{eq} = $1.75h$–$2.0h$. In the process of a phased increase in the vertical load after the formation of normal cracks in the zone of pure bending, the appearance of inclined cracks in the sup- port zone was observed. In the stage of accelerated opening of inclined cracks up to 3 mm, the destruction of the support zone occurred. After removing the reinforcement from the meshes, a crushing of the compressed concrete between the grids was detected. Strengthening of the support zone with vertical or inclined polymeric meshes led to a doubling of the strength of inclined cross-sections, and the strains of the fiber-reinforced meshes were 3–4 %. Along with the conventional scheme of the destruction of inclined cross-sections, an additional destruction scheme caused by the chipping of the protective layer of concrete under the strips of reinforcement nets was revealed. At the same time, the increase in strength did not exceed 50 %, and the largest strains of the meshes for the stage before the destruction were 1.8–2.5 %.

3.4. Discussion

Based on the results obtained from static tests (Fig. 9, *b*), it was determined that the strengthening of beams by gluing one layer of laminate on the stretched zone led to an increase in strength by 75 %. Strains of stretched steel reinforcement decreased by almost 10 %. This is due to an increase in the strength of the stretched reinforcement.

Our static tests were performed when the samples were loaded with a hydraulic jack (Fig. 4). The destruction of reinforced concrete beams without reinforcement was caused by the crushing of the compressed concrete zone in the zone of pure bending with the fluidity of the stretched steel reinforcement. When reinforcing the beams in the stretched zone with laminate tapes, along with the conventional scheme of the destruction of reinforced concrete structures, additional destruction schemes were revealed caused by the separation of the protective layer of concrete in the stretched zone or the separation of stretched laminate tapes from concrete. At the same time, an increase in the crack resistance and stiffness of normal sections was observed (Fig. 6). Taking into consideration the separation of the protective layer of concrete in the stretched zone, when calculating the required lifting of damaged reinforced concrete structures for their restoration, it is necessary to take the initial stiffness of the elements.

We identified options for the restoration of damaged reinforced concrete elements. Namely, the replacement of reinforcing rods [3], prone to corrosion, with rods made of composite material, strengthening reinforced concrete structures with composite plastics to increase their bearing capacity. Since materials have different bending moments, there was a separation of the protective layer of concrete from composite materials, which creates difficulties in studying and calculating.

In the future, other methods will be considered to advance the study into the work of FRP. Including the addition of fibers to the composition of concrete to increase their ability to bend in a stretched area.

4. Conclusion

1. The dynamic strength at cyclic loading of normal cross-sections of bendable elements strengthened in a stretched beam at a single load exceeded the static strength by 33 %. With an increase in the number of cyclic loads required for destruction from 2 to 280, the strains of the stretched laminate ranged from 1.88 ‰ to 2.05 ‰, and the vertical deflections increased by 26 %. Overall, the greatest strains of stretched laminate under dynamic loads were 45 % less than the strains of stretched laminate in static tests. The nature of the destruction of normal cross-sections of beams under dynamic loading differed little from the destruction of similar beams under static loading.

2. Prototypes were tested according to the scheme of a single-span hinged beam loaded in the span. Testing of the beams involved several stages of loading with unloading at different levels of force. Our results confirm the linear dependence of the relative height of the compressed concrete zone on the percentage of longitudinal reinforcement of the stretched zone.

3. When designing the restoration of normal cross-sections of damaged reinforced concrete structures with prestressed surface reinforcement with fiber-reinforced plastics, the following prerequisites should be met:

- when calculating the amount of required lifting of damaged reinforced concrete elements, take the initial stiffness of the intact element;
- the residual width of the opening of normal cracks when constructing an artificial construction lift, equivalent to the natural weight of the element being restored, should be taken to be equal to $a = 0.05–0.10$ mm;
- in most restored reinforced concrete structures, the residual opening width of normal cracks was about 50 % of the opening width of the existing cracks.

4. When designing the restoration of inclined sections of damaged reinforced concrete structures with prestressed surface reinforcement with fiber-reinforced plastics, the following prerequisites should be met:

- when calculating the amount of required lifting of damaged reinforced concrete elements, take the initial stiffness of the intact element;
- the estimated strength of the glued fiber-reinforced plastics must provide the strength of the inclined sections, exceeding the required strength of the inclined sections by 20 %;
- in most restored reinforced concrete structures, the residual opening width of the inclined cracks should not be less than $a = 0.20$ mm.

References

1. Krassowska, J., Piña, C. Flexural Capacity of Concrete Beams with Basalt Fiber-Reinforced Polymer Bars and Stirrups. Materials. 2022. 15 (22). 8270. DOI: 10.3390/ma15228270
2. Täljsten, B., Blanksvärd, T. Mineral-Based Bonding of Carbon FRP to Strengthen Concrete Structures. Journal of Composites for Construction. 2007. 11. Pp. 120–128. DOI: 10.1061/(ASCE)1090-0268(2007)11:2(120)
3. Chen, J., Teng, J. Anchorage strength models for FRP and steel plates bonded to concrete. Journal of Structural Engineering. 2001. 127. Pp. 784–791. DOI: 10.1061/(ASCE)0733-9445(2001)127:7(784)
4. Lu, X., Teng, J., Ye, L., Jiang, J. Bond–slip models for FRP sheets/plates bonded to concrete. Engineering Structures. 2005. 27. Pp. 920–937. DOI: 10.1016/j.engstruct.2005.01.014
5. Teng, J., Smith, S., Yao, J., Chen, J., Intermediate crack-induced debonding in RC beams and slabs. Construction and Building Materials. 2003. 17. Pp. 447–462. DOI: 10.1016/S0950-0618(03)00043-6
6. Dai, J., Ueda, T., Sato, Y. Development of the Nonlinear Bond Stress–Slip Model of Fiber Reinforced Plastics Sheet–Concrete Interfaces with a Simple Method. Journal of Composites for Construction. 2005. 9. Pp. 52–62. DOI: 10.1061/(ASCE)1090-0268(2005)9:1(52)
7. Sas, G., Täljsten, B., Barros, J., Lima, J., Carolin, A. Are Available Models Reliable for Predicting the FRP Contribution to the Shear Resistance of RC Beams? Journal of Composites for Construction. 2009. 13. Pp. 514–534. DOI: 10.1061/(ASCE)CC.1943-5614.0000045

8. Kotynia, R., Abdel Baky, H., Neale, K., Ebead, U. Flexural Strengthening of RC Beams with Externally Bonded CFRP Systems: Test Results and 3D Nonlinear FE Analysis. Journal of Composites for Construction. 2008. 12. Pp. 190–201. DOI: 10.1061/(ASCE)1090-0268(2008)12:2(190)
9. Triantafillou, T. Shear Strengthening of Reinforced Concrete Beams Using Epoxy Bonded FRP Composites. Structure Journal. 1998. 95. Pp. 107–115. DOI: 10.14359/531
10. Bespayev, A., Altigenov, U., Kuralov, U. Usileniye i vosstanovleniye izgibayemykh zhelezobetonnykh konstruktsiy predvaritelno napryazhennymi fibroarmirovannymi plastikami. Nauka i innovatsionnyye tekhnologii. 2018. 3 (8). Pp. 154–156.
11. El-Hacha, R., Wight, R., Green, M. Innovative System for Prestressing Fiber-Reinforced Polymer Sheets. Structure Journal. 2003. 100. Pp. 305–313.
12. Täljsten B. Defining anchor lengths of steel and CFRP plates bonded to concrete. International Journal of Adhesion and Adhesives. 1997. 17. Pp. 319–327. DOI: 10.1016/S0143-7496(97)00018-3
13. Banthia, N., Boyd, A. Sprayed fibre-reinforced polymers for repairs. Canadian Journal of Civil Engineering. 2000. 27. DOI: 10.1139/l00-027
14. Mukhanbetzhanova, Zh., Bespayev, A. Metod usileniya zhelezobetonnykh konstruktsiy, povrezhdennykh pri raznykh faktorakh. QazBSQA Khabarshysy. Құrylys konstruktsiyalary zhәne materialdary. 2022. 2 (84). Pp. 263–269. DOI: 10.51488/1680-080X/2022.2-19
15. Bespayev, A., Kuralov U., Altigenov U. Usileniye zhelezobetonnykh konstruktsiy polimernymi materialami. Vestnik Natsionalnoy inzhenernoy akademii RK. 2011. 2. Pp. 115–118.
16. Bespayev, A., Kuralov, U., Altigenov, U. The strengthening and renewing of damaged reinforced concrete structures by restressed fiber reinforced plastics. International scientific conference. Machines. Technologies. Materials. 2019. 3 (14).
17. Nawaz, W., Elchalakani, M., Yehia, Sh., Pham Th. The effect of CFRP strip stirrups on the shear strength of SCC high strength lightweight concrete beams. Structures. 2022. 47 (1). Pp. 709–724. DOI: 10.1016/j.istruc.2022.11.026
18. Aydın, E., Boru E., Aydın, F. Effects of FRP bar type and fiber reinforced concrete in the flexural behavior of hybrid beams. Construction and Building Materials. 2021. 279. 122407. DOI: 10.1016/j.conbuildmat.2021.122407
19. Tang, Y., Jiang, T., Wan, W. Structural monitoring method for RC column with distributed self-sensing BFRP bars. Case Studies in Construction Materials. 2022. 17. E01616. DOI: 10.1016/j.cscm.2022.e01616
20. Bakis, C., Bank, L., Brown, V., Cosenza, E., Davalos, J., Lesko, J. Fiber-Reinforced Polymer Composites for Construction. Journal of Composite Construction. 2002. 6. Pp. 73–87. DOI: 10.1061/(ASCE)1090-0268(2002)6:2(73)
21. Elchalakani, M., Yang, B., Mao, K., Pham, Th. Mechanical properties of fiber reinforced polymer (FRP) and steel bars. Geopolymer Concrete Structures with Steel and FRP Reinforcements. 2022. Pp. 75–135. DOI: 10.1016/B978-0-443-18876-3.00002-5
22. Hollaway, L. A review of the present and future utilization of FRP composites in the civil infrastructure with reference to their important in-service properties. Construction and Building Materials. 2010. 24. Pp. 2419–45. DOI: 10.1016/j.conbuildmat.2010.04.062
23. Yang, J., Haghani, R., Blanksvärd, T., Lundgren, K. Experimental study of FRP-strengthened concrete beams with corroded reinforcement. Construction and Building Materials. 2021. 301. 124076. DOI: 10.1016/j.conbuildmat.2021.124076
24. Zhou, J., Li, Ch., Yoo, D., He J., Feng, Zh. Modified softened membrane model for ultra-hogh-performance fiber-reinforced concrete solid and hollow beams under pure torsion. Engineering Structures. 2022. 270. 114865. DOI: 10.1016/j.engstruct.2022.114865
25. Lin, X., Zhang, Y. Bond–slip behaviour of FRP-reinforced concrete beams. Construction and Building Materials. 2013. 44. Pp. 110–117. DOI: 10.1016/j.conbuildmat.2013.03.023
26. Triantafyllou, G., Rousakis, T., Karabinis, A. Effect of patch repair and strengthening with EBR and NSM CFRP laminates for RC beams with low, medium and heavy corrosion. Composites Part B Engineering. 2018. 133. DOI: 10.1016/j.compositesb.2017.09.029
27. Singh, S. Shear response and design of RC beams strengthened using CFRP laminates. International Journal of Advanced Structural Engineering. 2013. 5 (1). DOI: 10.1186/2008-6695-5-16
28. Fu, B., Tang, X., Li, L., Liu, F., Lin, G. Inclined FRP U-jackets for enhancing structural performance of FRP-plated RC beams suffering from IC debonding. Composite Structures. 2018. 200. Pp. 36–46. DOI: 10.1016/j.compstruct.2018.05.074
29. Hussein, M., Afefy, H., Khalil, A-H. Innovative repair technique for RC beams predamaged in shear. Journal of composites for construction. 2013. 17. DOI: 10.1061/%28ASCE%29CC.1943-5614.0000404
30. Campione, G., Minafò, G. Behaviour of concrete deep beams with openings and low shear span-to-depth ratio. Engineering Structures. 2012. 41. Pp. 294–306. DOI: 10.1016/j.engstruct.2012.03.055
31. Hussain, Q., Pimanmas, A. Shear strengthening of RC deep beams with openings using sprayed glass fiber reinforced polymer composites (SGFRP): Part 1, Experimental study. KSCE Journal of Civil engineering. 2015. 19. Pp. 2121–2133. DOI: 10.1007/s12205-015-0243-1

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