Theory and Building Practice

Vol. 6, No. 2, 2024

https://doi.org/ 10.23939/jtbp2024.02.096

Illia Lytvynenko, Yaroslav Blikharskyy

COMPOSITE MATERIALS FOR STRENGTHENING OF REINFORCED CONCRETE STRUCTURES – A REVIEW

Lviv Polytechnic National University
Department of Highways and bridges
yaroslav.z.blikharskyy@lpnu.ua

Ó *Lytvynenko I., Blikharskyy Y., 2024*

This article presents a study of the use of composite materials in strengthening building structures. Materials consisting of two or more components or phases are called composite. Now modern composite materials open up new opportunities for design in all areas of production. The construction industry is no exception. Laminates, canvases, nets, rebars and ropes made of high-strength fibers of various origins are among the most widely used in construction at the moment. The main components of any composite are high-strength fibers that absorb the load, and a stabilizing matrix that serves to transfer forces to the fibers. The following types of high-strength fibers are used in composites: glass fibers, carbon fibers, organic fibers, silicon-carbon, aluminum-silicon fibers, and others. With the help of composite reinforcement, it is possible to effectively strengthen normal and inclined sections of reinforced concrete structures.

Key words: bending moment, transverse force, composite materials, reinforcement, reinforced concrete structures, polymers.

Introduction

There are many definitions of composite materials in the literature, in particular: materials consisting of two or more components or phases are called composite (Yao et al., 2019); a composite material is a combination of two or more materials, the result of which is better properties of the original material compared to the properties of each ingredient separately (Biswal and Swain, 2020); in composites, materials are combined in such a way as to maximize their advantages while minimizing their disadvantages (Huang et al., 2023).

Today, modern composite materials open new opportunities for design in all areas of production (Aziz et al., 2023; Egbo, 2021; Hsissou et al., 2021). The construction industry is no exception. Laminates, webs, meshes, reinforcing bars and ropes made of high-strength fibers of various origins are among the most widely used in construction at the moment (Abavisani et al., 2021; Mukherjee et al., 2023; Zhang et al., 2020).

The main components of any composite are high-strength fibers that absorb the load, and a stabilizing matrix that serves to transfer forces to the fibers. The following types of high-strength fibers are used in composites: glass fibers, carbon fibers, organic fibers (aramid), silicon-carbon, aluminum-silicon fibers, and others (Godara et al., 2021). The matrix can be: polymers, metals, glass, ceramics, cement mortar, carbon in different phases (Gupta et al., 2021).

However, composite materials with polymer FRP (Fiber Reinforced Polymer) or cement FRC (Fiber Reinforced Cement) matrixes, as well as non-metallic reinforcement rods are most often used to solve the problems of strengthening building structures, so in the future we will focus our attention on them. Historically, FRP composites were the first to emerge and become widespread, so currently a lot of research on these materials has been published. However, considering a number of disadvantages of polymers as a stabilizing matrix, researchers began to develop and research new inorganic matrices based on cement binders. This is how FRC composites appeared.

Application of modern composites in construction

Considering the fact that fiberglass or carbon fiber reinforcement has a strength 3–6 times higher than the strength of reinforcing steel, they were tried to be used in long-span structures. For example, in 1978, prestressed rods of fiberglass reinforcement were used in the load-bearing structures of a pedestrian bridge in Dusseldorf (Burgoyne, 1999). For this experiment, special anchors were developed in the form of steel pipes, in which the stressed rods were fixed with the help of epoxy. At the same time, similar experiments were conducted in Holland with reinforcement based on aramid fibers. In both cases, it was concluded that this method of anchoring is not suitable for structures under long-term load, since the stress on the reinforcement is transmitted through epoxy resin, which is prone to creep and temperature effects.

Over time, ideas about the use of carbon fiber cables in long-span bridges appeared more often. Taking into account the need for the joint operation of individual rods in the cable, special anchor blocks were developed (Meier and Farshad, 1996). In order to avoid the concentration of stresses at the exit of the rods from the anchor, a fixing resin with lower stiffness was used, layer by layer changing it to a stiffer one in the depth of the anchor block.

The use of cables made of carbon or aramid fibers opens up the possibility of designing long-span structures with a span of up to 10 km (Meier, 1987; Richmond and Head, 1988) under the condition of static loading, which is, of course, unrealistic considering the aerodynamic effects on such structures (Hay, 1992).

Considering the significant advantages of non-metallic reinforcement over metallic reinforcement in the context of corrosion resistance, in the late 1990s research was actively conducted on the use of non-metallic reinforcement in reinforced concrete structures (Buyle-Bodin et al., 1995; Hall and Mottram, 1998). For example, the Fidgett pedestrian bridge in Great Britain, built in 1995, became the first concrete structure completely reinforced with glass fiber reinforcement belonging to the group of GFRP (Glass Fiber Reinforced Polymer) composites. Fiber optic sensors and strain gauges were installed on the frame rod during concreting for long-term monitoring of the stress state of the bridge structures (O'Regan et al., 1996).

A similar experience of using GFRP for reinforcing concrete structures was observed in 1999 in the USA (Missouri) (Nanni, 2000). Here, precast concrete elements of a box profile, fully reinforced with GFRP rods, were used to replace steel pipes of a drainage channel under a road in the town of Rolla. Long-term monitoring of structures was provided with the help of fiber optic sensors on reinforcing frames.

Also noteworthy are studies funded by the US Federal Highway Administration in 2000, including work (Yan et al., 2000). The results of research on prestressed FRP composites for highway bridge structures are collected in three volumes. The research was conducted due to the fact that the existing methods of anti-corrosion protection of prestressed reinforced concrete structures do not give a completely satisfactory result. Therefore, the possibility of using FRP composites instead of reinforcing steel is being considered. (Yan et al., 2000) also consider the issue of manufacturing concrete structures with non-metallic prestressed reinforcement, since traditional methods of producing prestressed reinforced concrete structures are not suitable for FRP.

Paying attention to the results of research (Yan et al., 2000), which relate to tests of concrete beams with prestressed composite reinforcement and mixed reinforcement for bending under cyclic loading, it can be noted that the deformation of such samples has an elastic bilinear character. Before the appearance of the first cracks, the curvature and deflection of the beams varied according to a linear law as a function of the stiffness of the full section. After the appearance of normal cracks in the zone of pure bending, which led to a decrease in the stiffness of the cross-section, the beam underwent significant deflections according to the load, but the character of the deformation remained linear until failure. During unloading, a significant reduction in deflection was observed, which is an advantage from an operational point of view, but can be a disadvantage in terms of energy absorption. Both in the case of prestressed beams and in the case of samples with mixed reinforcement, the failure occurred as a result of the rupture of the prestressed bars and had an instantaneous explosive nature.

Prestressing of externally fixed composites

Considering the high strength of FRP laminates, it is almost impossible to fully use their strength. Prestressing can make it possible to use the strength properties of the material more effectively, as well as have a positive effect on the deformability and crack resistance of the reinforced structure.

There are three methods of prestressing externally fixed composites (Jokūbaitis and Valivonis, 2022):

- fastening to a structure with reverse bending;
- tension with jacks directly on the structure;
- tension with jacks on the fixing frame.

All these methods can be applied in practice when strengthening bent elements, but the process of prestressing significantly increases the complexity of strengthening, the number of operations and the duration of the process.

In the work (Wight et al., 2001), a bending test of conventional reinforced concrete beams and beams reinforced with stressed and unstressed webs based on carbon fibers was carried out. The authors came to the conclusion that the prestress has the greatest effect on the crack resistance of the beam. Thanks to the reduced deflections and curvature of the beams, the deformation of the reinforcement reaches the limit values at loads that are 35–40 % higher compared to unreinforced samples.

The test results given in (Yu et al., 2003) show that with the help of prestressing and reliable anchoring, it is possible to achieve a reduction in the maximum beam deflection of up to 75 %. It was also established that the relative deformations of the web before the appearance of the first cracks are close to zero. The nature of the destruction of samples reinforced with stressed and unstressed fabric also differed. The destruction of unstressed specimens occurred due to the rupture of the reinforcement, and in the case of stressed specimens – due to the detachment of the anchor. Therefore, anchoring of prestressed composites is mandatory.

In the works (Wight et al., 2001; Yu et al., 2003), the reinforcement was carried out along the lower face of the beams outside the test stand, which allowed almost full use of the surface area of the lower face between the supports. Taking into account the space required for prestressing equipment, it becomes obvious that in real conditions it is impossible to fully use this area. The ends of the composite will be separated from the supports (columns, walls) by an amount that depends on the dimensions of the equipment for stressing the reinforcement elements. This, in turn, leads to the fact that the probable nature of the destruction will be the delamination of the composite from the core to the center.

Taking into account these features, the tests of branded beams in the work were carried out (Wang, 2001). The beams were reinforced with stressed CFRP laminates. Tension was performed by tensioning the structure with the help of jacks. The reinforcement was installed symmetrically on the side edges of the beam edge, which allowed a partial gain in the length of the laminate. The metal plates used to install the jacks were later used as mechanical anchors. The destruction of the beam occurred after the laminate slipped under one of the anchors. At the same time, the relative deformations of the laminate were 70 % of the limit ones. An important observation was that after the fluidity of the working armature, the reduction in shear stiffness was smooth. This is evidence of plastic deformation of the structure, which is not characteristic of reinforced concrete elements reinforced by externally attached composites.

The above discussed system of anchoring the webs with fiberglass anchors (Piyong et al., 2003) made it possible to achieve reliable anchoring of the prestressed CFRP webs without slipping or peeling until their rupture. As a result, a significant reduction in the deformability of the reinforced plate was achieved. When the forces in the armature of the non-reinforced plate were $0.7f_y$, its deflection was 2.8 cm. Under the same load, the deflection of the reinforced plate was practically zero. Such a result was achieved only because the prestressing was carried out due to the reverse bending of the structure, which is practically impossible in the conditions of real operation of the structure.

Increasing seismic resistance using externally fixed composites

The progressive development of regulatory documents in the field of design and construction places higher and higher requirements on structures. This applies both to the calculation of structures and to the structural requirements for them. The area of earthquake-resistant design is no exception. With the introduction of new normative documents on earthquake resistance, almost all previously designed structures did not meet the increased requirements of these rules. That is why practically every project of strengthening or reconstruction of buildings and structures should include increasing the seismic resistance of structures and structures as a whole.

Given the wide interest of researchers in modern composites, the question of using these materials to increase seismic resistance arose. Field tests of the reinforced concrete frame of the freeway were carried out by the authors of the work (Pantelides and Gergely, 2008). Tests of the reinforced and unreinforced two-span frame for horizontal cyclic loads were performed. Reinforcement was carried out in the form of a CFRP clip in the places where the columns are embedded in the foundation, in the joints of the columns with a continuous crossbar and in the zone of maximum transverse force in the crossbar. Recording of hysteresis curves showed that the ability of the reinforced frame to absorb energy increased due to additional plastic deformations. The authors come to the conclusion that this type of reinforcement can solve the following problems: insufficient transverse reinforcement of columns and joints of columns with a transom; insufficient anchoring of the working armature of the column in the crossbar; presence of welded clamps instead of knitted ones; the length of the seam is too short when welding the reinforcement in the opening. At the same time, the authors note that the strengthening should be carried out as a complex for the entire structure, since the strengthening of individual parts can cause the weakening of others.

Similar results were obtained by the authors of the work (Triantafillou, 2001) after laboratory tests of the joints of reinforced concrete columns with crossbars. The researchers came to the conclusion that CFRP clips significantly increase the deformability of structures, that is, they allow the occurrence of significant movements or turns of the section. This, in turn, allows the formation of plasticity hinges and prevents brittle destruction of structures. It was also found that the clamps are more effective in the case of round columns compared to rectangular ones, since there is no stress concentration at the corners. Similar to (Pantelides and Gergely, 2008), it was established that the lack of transverse reinforcement of the joints of columns with crossbars can be compensated for with a CFRP clip.

Conclusions

- Concrete structures reinforced with non-metallic composite reinforcement are not yet used in the construction of responsible structures due to insufficient performance of such structures;
- the nature of deformation and destruction of structures reinforced with composite reinforcement differs from the nature of deformation and destruction of reinforced concrete structures due to the different physical and mechanical characteristics of metallic and non-metallic reinforcement;
- concrete structures reinforced with non-metallic composite reinforcement have low plasticity, which is a negative factor in seismic impacts;
- with the help of composite reinforcement, it is possible to effectively strengthen normal and inclined sections of reinforced concrete structures;
- reliable anchoring of composites has a positive effect on the deformability of the reinforced structure;
- canvases or laminates are included in joint work with the structure after the appearance of cracks in it;
- pre-tensioning of composite materials complicates the strengthening process, but increases crack resistance and reduces deformability of structures;
- carbon fiber clips can effectively increase the seismic resistance of reinforced concrete structures.

Acknowledgments

This work was supported by the National Research Foundation of Ukraine (Grant No. 2023.05/0026).

References

Yao, J., Zhou, Z., Zhou, H., Yao, J., Zhou, Z., & Zhou, H. (2019). Introduction to composite materials. Highway Engineering Composite Material and Its Application, 1–23. https://doi.org/10.1007/978-981-13-6068-8_1

Biswal, A., & Swain, S. K. (2020). Smart composite materials for civil engineering applications. In Polymer nanocomposite-based smart materials, 197–210. https://doi.org/10.1016/B978-0-08-103013-4.00011-X

Huang, X., Su, S., Xu, Z., Miao, Q., Li, W., & Wang, L. (2023). Advanced composite materials for structure strengthening and resilience improvement. *Buildings*, 13(10), 2406. https://doi.org/10.3390/buildings13102406

Zhang, P., Han, S., Golewski, G. L., & Wang, X. (2020). Nanoparticle-reinforced building materials with applications in civil engineering. *Advances in Mechanical Engineering*, 12(10), 1687814020965438. https://doi.org/10.1177/1687814020965438

Abavisani, I., Rezaifar, O., & Kheyroddin, A. (2021). Multifunctional properties of shape memory materials in civil engineering applications: A state-of-the-art review. *Journal of Building Engineering*, 44, 102657. https://doi.org/10.1016/j.jobe.2021.102657

Mukherjee, A., Srivastava, P., & Sandhu, J. K. (2023). Application of smart materials in civil engineering: A review. *Materials Today: Proceedings*, 81, 350–359. https://doi.org/10.1016/j.matpr.2021.03.304

Egbo, M. K. (2021). A fundamental review on composite materials and some of their applications in biomedical engineering. Journal of King Saud University-Engineering Sciences, 33(8), 557-568. https://doi.org/10.1016/j.jksues.2020.07.007

Aziz, T., Haq, F., Farid, A., Kiran, M., Faisal, S., Ullah, A., ... & Show, P. L. (2023). Challenges associated with cellulose composite material: Facet engineering and prospective. *Environmental Research*, 223, 115429. https://doi.org/10.1016/j.envres.2023.115429

Hsissou, R., Seghiri, R., Benzekri, Z., Hilali, M., Rafik, M., & Elharfi, A. (2021). Polymer composite materials: A comprehensive review. *Composite structures*, 262, 113640. https://doi.org/10.1016/j.compstruct.2021.113640

Godara, S. S., Yadav, A., Goswami, B., & Rana, R. S. (2021). Review on history and characterization of polymer composite materials. *Materials Today: Proceedings*, 44, 2674–2677. https://doi.org/10.1016 /j.matpr.2020.12.680

Gupta, R., Mitchell, D., Blanche, J., Harper, S., Tang, W., Pancholi, K., ... & Flynn, D. (2021). A review of sensing technologies for non-destructive evaluation of structural composite materials. *Journal of Composites Science*, 5(12), 319. https://doi.org/10.3390/jcs5120319

Burgoyne, C. J. (1999). Advanced composites in civil engineering in Europe. *Structural Engineering International*, 9(4), 267–273. https://doi.org/10.2749/101686699780481682

Meier, U., & Farshad, M. (1996). Connecting high-performance carbon-fiber-reinforced polymer cables of suspension and cable-stayed bridges through the use of gradient materials. *Journal of Computer-Aided Materials Design*, 3, 379–384.

Meier, U. (1987). Proposal for a carbon fibre reinforced composite bridge across the Strait of Gibraltar at its narrowest site. Proceedings of the Institution of Mechanical Engineers, Part B: Management and engineering manufacture, 201(2), 73–78. https://doi.org/10.1243/PIME_PROC_1987_201_048_02

Richmond, R., & Head, P. R. (1988, June). Alternative materials in long-span bridge structures. In Proceedings of the 1st Oleg Kerensky Memorial Conference on Tension Structures, London. https://www.istructe.org/journal/volumes/volume-66-(published-in-1988)/issue-12/1st-international-oleg-kerensky-memorial-conferenc/

Hay, J. (1992). Response of bridges to wind. Her majesty's stationery office, London, UK. 179 p. https://trid.trb.org/View/376925

Buyle-Bodin, F., Benhouna, M., & Convain, M. (1995, August). 28 Flexural behaviour of JITEC-FRP reinforced beams. In Non-Metallic (FRP) Reinforcement for Concrete Structures: Proceedings of the Second International RILEM Symposium (Vol. 29, p. 235). CRC Press. https://books.google.com/books?hl=uk&lr=&id=8Xe-n2zA_nMC&oi=fnd&pg=PA235&dq=Flexural+Behaviour+of+JITECFRP+Reinforced+beams+&ots=_im8XziSpf&sig=5d1FZWwxdQKRTvn1qxCYCnYWIWU

Hall, J. E., & Mottram, J. T. (1998). Combined FRP reinforcement and permanent formwork for concrete members. *Journal of Composites for Construction*, 2(2), 78–86. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:2(78)

O'Regan, D. P., Clarke, J. L., & Dill, M. J. (1996). Site testing and monitoring of Fidgett Footbridge. *Construction repair*, 10(5), p. 29–31. https://trid.trb.org/View/469595

Nanni, A. (2000, March). FRP reinforcement for bridge structures. In Proceedings of Structural Engineering Conference. The University of Kansas, Lawrence, KS (p. 5). https://quakewrap.com/frp%20papers/FRP-Reinforcement-for-Bridge-Structures.pdf

Yan, X., Myers, J. J., & Nanni, A. (2000). An assessment of flexural behavior of CFRP prestressed beams subjected to incremental static loading. In ASCE Structures Congress. https://works.bepress.com/john-myers/cv/download/

Tahsiri, H., & Belarbi, A. (2022). Evaluation of prestress relaxation loss and harping characteristics of prestressing CFRP systems. *Construction and Building* Materials, 331, 127339.

Jokūbaitis, A., & Valivonis, J. (2022). An analysis of the transfer lengths of different types of prestressed fiber-reinforced polymer reinforcement. *Polymers*, 14(19), 3931. https://doi.org/10.3390/polym14193931

Wight, R. G., Green, M. F., & Erki, M. A. (2001). Prestressed FRP sheets for poststrengthening reinforced concrete beams. *Journal of composites for construction*, 5(4), 214–220. https://doi.org/10.1061/(ASCE)1090-0268(2001)5:4(214)

Yu, P., Silva, P. F., & Nanni, A. (2003). Flexural performance of RC beams strengthened with prestressed CFRP sheets. Center for Infrastructure and Engineering Studies Department of Civil, Architectural, and Environmental Engineering University of Missouri-Rolla Rolla, MO, 65409-0030. https://www.researchgate.net/profile/Antonio-Nanni-3/publication/237445119_FLEXURAL_PERFORMANCE_OF_RC_BEAMS_STRENGTHENED_WITH_PRESTRES-SED_CFRP_SHEETS/links/00b495321cf3e024da000000/FLEXURAL-PERFORMANCE-OF-RC-BEAMS-STRENGTHENED-WITH-PRESTRESSED-CFRP-SHEETS.pdf

Wang, H. T., Liu, S. S., Zhu, C. Y., Xiong, H., & Xu, G. W. (2022). Experimental study on the flexural behavior of large-scale reinforced concrete beams strengthened with prestressed CFRP plates. *Journal of Composites for Construction*, 26(6), 04022076. https://doi.org/10.1061/(ASCE)CC.1943–5614.0001267

Piyong, Y., Silva, P. F., & Nanni, A. (2003, September). Flexural strengthening of concrete slabs by a three-stage prestressing FRP system enhanced with the presence of GFRP anchor spikes. In Proceedings of the International Conference Composites in Construction (CCC2003) (Vol. 239244). University of Calabria Rende, Italy. https://quakewrap.com/frp%20papers/FlexuralStrengtheningofConcreteSlabbyPrestressingFRPLamina-teswiththePresenceofGFRPAnchorSpikes.pdf

Pantelides, C. P., & Gergely, J. (2008). Seismic retrofit of reinforced concrete beam-column T-joints in bridge piers with FRP composite jackets. Seismic Strengthening of Concrete Buildings Using FRP Composites, 258, 7. https://books.google.com/books?hl=uk&lr=&id=gI72a6OHeQIC&oi=fnd&pg=PA7&dq=Seismic+retrofit+of+reinfor-ced+concrete+beam-column+T-joints+in+bridge+piers+with+FRP+composite+jackets+&ots=J0t7cKWu78&sig=IioIphImLbGzlr1J7oD87JNkll8

Triantafillou, T. C. (2001). Seismic retrofitting of structures with fibre-reinforced polymers. *Progress in Structural Engineering and Materials*, 3(1), 57–65. https://doi.org/10.1002/pse.61

І. Ю. Литвиненко, Я. З. Біхарський
Національний університет “Львівська політехніка”,
кафедра автомобільних доріг та мостів

КОМПОЗИТНІ МАТЕРІАЛИ ДЛЯ ПІДСИЛЕННЯ ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ - ОГЛЯД

Ó *Литвиненко І. Ю., Біхарський Я. З., 2024*

У статті досліджено застосування композитних матеріалів для підсилення та відновлення будівельних конструкцій. Композитними називають матеріали, котрі складаються з двох чи більше компонентів чи фаз. Серед найвживаніших у будівництві на нині є ламінати, полотна, сітки, арматурні стержні та канати, виготовлені з високоміцних волокон різного походження. Основними компонентами будь-якого композиту є високоміцні волокна, котрі сприймають навантаження, і стабілізувальна матриця призначена для передавання зусиль на волокна. У композитах застосовують такі види високоміцних волокон: скловолокна, вуглецеві волокна, органічні волокна, силіконо-вуглецеві, алюмінієво-силіконові волокна та інші. Матрицею можуть бути: полімери, метали, скло, кераміка, цементний розчин, вуглець у різних фазах. Для вирішення проблем підсилення будівельних конструкцій найчастіше користуються композитними матеріалами з полімерною Fiber Reinforced Polymer чи цементною Fiber Reinforced Cement матрицями, а також стержнями неметалевої арматури, тому надалі зосередимо свою увагу саме на них. Історично першими виникли та набули поширення FRP композити, тому уже опубліковано дуже багато досліджень цих матеріалів. Проте, зважаючи на низку недоліків полімерів як стабілізувальної матриці, дослідники почали розробляти та досліджувати нові неорганічні матриці на основі цементних в’яжучих. Так з’явились FRC композити. Бетонні конструкції армовані неметалевою композитною арматурою поки що не застосовують у будівництві відповідальних споруд через недостатню роботу таких конструкцій.Деформування та руйнування конструкцій, армованих композитною арматурою, відрізняється від деформування та руйнування залізобетонних конструкцій унаслідок відмінних фізико-механічних характеристик металевої та неметалевої арматури.

Ключові слова: згинальний момент, поперечна сила, композитні матеріали, підсилення, залізобетонні конструкції, полімери.