

Structural Mechanics Aspect of Strength of Composite Reinforcement

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Abstract. When operating in wet and corrosive conditions, composite reinforcement is in some cases an effective substitute for the suitable steel reinforcement. However, many questions related to its design, production and operation are insufficiently studied. The aim of the work is to create a methodology and carry out a comparative structural and mechanical analysis of strength indexes when working under load of coils and a bar of composite construction reinforcement. A method has been developed for analyzing the loading capacity of composite reinforcement according to the criteria of strength at rupture of a bar, as well as shear strength and bearing strength of its braid coils. Analytical and numerical modeling of conditions of equal strength of structural elements of composite construction reinforcement was carried out. Theoretically substantiated the assumption of a relatively low loading capacity of the braid coils in comparison with the loading capacity of the reinforcement bar. A predictive estimate of the conditions for ensuring the uniform strength of the bar for breaking and braid coils for shear and crushing by the method of lower estimation (for the minimum values of strength) has been carried out using the example of composite reinforcing bars produced by the industry of Republic of Belarus. In conclusion, results of work are formulated and it is noted that the results can be used by manufacturers and consumers of construction composite reinforcement, also in the educational process in the training of engineering personnel for the construction profile.

Keywords: composite reinforcement, coils, bar, strength, shear, breaking force, crushing.

Introduction.

Steel reinforcement traditionally used in the production of reinforced concrete has a number of disadvantages, the most important of which are low corrosion resistance, as well as the relatively high specific gravity and thermal conductivity of the metal. In the Russian Federation [1–4], in the Republic of Belarus [5–10] and many scientific and technical centers of foreign countries [11–13], research and development is being carried out aimed at creating composite reinforcing materials based on high-strength fibers and polymer matrixes. Research and development are carried out both in relation to composites based on glass and basalt fibers that have already become traditional [14–16], and in the direction of creating hybrid composites that simultaneously include several types of reinforcing fibers (glass + carbon, glass + aramid) [11, 17–23].

Taking into account the economic side of the problem, polymer composites based on glass and basalt fibers are the most promising in the construction, transport and household spheres. However, the widespread use of such materials is hindered by a number of factors, among which one can single out [8, 9] the lack of study of the work under load both a whole composite construction reinforcement, and its individual elements (bar, coils, braids), as well as the lack of a regulatory framework for assigning mechanical characteristics, control and testing methods.

For example, it is known that in steel reinforcement the ribs on the surface of the bars provide high-quality adhesion of the reinforcement of a helical, crescent-shaped or other periodic profile to concrete and contribute to an increase in the reinforcing effect of the bars [24]. In composite reinforcement, braid coils can act as an analogue of corrugations. However, their work under load has not been adequately studied, there are no **methods for comparative predictive estimate of strength indexes**, and scientifically grounded recommendations on the appointment of winding parameters have not been developed. All this makes it difficult to predict the performance in terms of the strength of building structures containing composite reinforcement.

The aim of the research is to create a methodology and carry out a comparative analysis of strength indexes working under a load of coils and a bar of composite construction reinforcement.

Methodology of predictive estimate of the braid coils strength indexes.

Coils of composite reinforcement work under longitudinal loading (tension of a bar surrounded by hardened concrete) on a shear at the matrix (in the zone of adhesion to the bar) and on crushing of the side surfaces. To draw up the design scheme, we will perform a sweeping of a cylindrical part of the bar with coils. As a result, we get a rectangle with a base equal to the circumference ($L = \pi d$), on which inclined stripes are applied, characterizing the sweep of the spiral braid (Fig. 1).

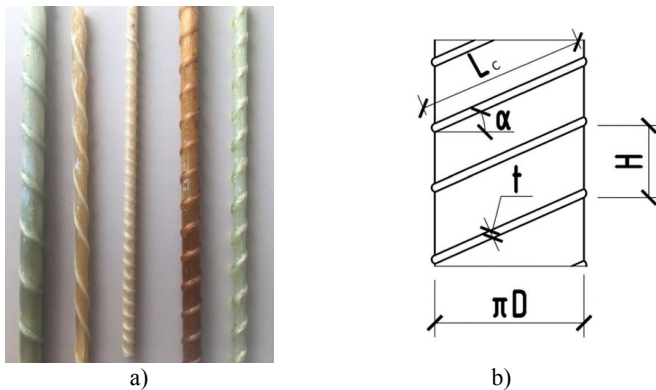


Fig. 1. General view (a) and the surface sweep (b) of the composite reinforcement.

It can be seen from the surface sweep that the length L_c of a coil (spiral line) for a composite reinforcement bar with a core diameter d , on which the braid is wound at an angle α with a winding step H , can be determined by the following formula:

$$L_c = \frac{\pi d}{\cos \alpha} = \sqrt{(\pi d)^2 + H^2} \quad (1)$$

The area A_c of the coil base with the bar connecting is equal to the product of the coil spiral line length L_c by the coil width t at the base:

$$A_c = \frac{\pi d}{\cos \alpha} t = t \sqrt{(\pi d)^2 + H^2} \quad (2)$$

The one coil shear force F_s can be found as the product of the resin shear strength limit τ_s by the shear area which is equal to the cross-sectional area of the coil at the base A_c :

$$F_s = \tau_s A_c = \tau_s t \frac{\pi d}{\cos \alpha} = \tau_s t \sqrt{(\pi d)^2 + H^2} \quad (3)$$

Whence after removing the rod diameter d from under the radical we obtain:

$$F_s = \tau_s t d \sqrt{\pi^2 + \left(\frac{H}{d}\right)^2} \quad (4)$$

Shear force F_{sn} for n_s coils is:

$$F_{s_n} = n_s \tau_s t d \sqrt{\pi^2 + \left(\frac{H}{d}\right)^2} \quad (5)$$

The breaking force of the bar F_p is equal the product of own cross-sectional area on the bar material strength limit σ_b at break:

$$F_p = \sigma_p \frac{\pi d^2}{4} \quad (6)$$

As a result of equating the shearing force of the braid coil and the breaking force of the reinforcement bar we obtain:

$$\tau_s t d n_s \sqrt{\pi^2 + \left(\frac{H}{d}\right)^2} = \sigma_p \frac{\pi d^2}{4}$$

Whence the required number of winding coils n_s from the position of equal strength of the bar at breaking and coils per shearing:

$$n_s = \frac{\pi d}{4t \sqrt{\pi^2 + \left(\frac{H}{d}\right)^2}} \frac{\sigma_p}{\tau_s} \quad (7)$$

In addition to cutting off the coils at the base, the second reason for the loss of strength is the destruction of the coil surface due to its compressive breaking. The crushing force F_{bl} of one coil can be found as the product of the resin compressive strength σ_b and the crushing area which is equal to the product of the coil length L_c and the coil cross section height h :

$$F_{b1} = \sigma_b L_c = \sigma_b h d \sqrt{\pi^2 + \left(\frac{H}{d}\right)^2}. \quad (8)$$

The crushing force F_b for n_b coils is found as the product of the corresponding crushing force for one coil determined by formula (8) by the number of coils n_b :

$$F_b = n_b F_{b1} = \sigma_b h d n_b \sqrt{\pi^2 + \left(\frac{H}{d}\right)^2}. \quad (9)$$

As a result of equating the coil lateral surface crushing force and the breaking force of the composite reinforcement bar we obtain the required number of bars ensuring for the condition of equal strength of the bar breaking and coils crushing:

$$n_b = \frac{\pi d}{4h} \frac{\sigma_p}{\sqrt{\pi^2 + \left(\frac{H}{d}\right)^2} \sigma_b}. \quad (10)$$

Methodology for predictive estimate of the ultimate tensile strength for a composite structural reinforcement bar.

As can be seen from formulas (7) and (10), one of the most important factors determining the minimum required number of coils, which ensures the uniform strength of the elements of composite reinforcement to rupture of the bar, as well as shear and crushing of the braid coils, is the strength of the bar. Despite the seeming simplicity of the analysis, the problem of predicting the strength of unidirectional composites has so far been solved only in an approximate estimated formulation.

In a simplified theoretical analysis of the physical and mechanical properties of unidirectional composites, formulas based on the so-called “rule of mixtures” are usually used which for the elastic modulus and density of the composite bar have the following form [13]:

$$E_k = E_f \theta_f + E_m \theta_m = E_f \theta_f + E_m (1 - \theta_f) \quad (11)$$

$$\rho_k = \rho_f \theta_f + \rho_m \theta_m = \rho_f \theta_f + \rho_m (1 - \theta_f) \quad (12)$$

where E_k, E_f, E_m – elastic moduli of the composite reinforcing fiber and polymer binder (matrix) respectively; θ_f, θ_m – volumetric content of reinforcing fiber and binder respectively; ρ_k, ρ_f, ρ_m – respectively, density of the composite, fibers and binder.

In this case $\theta_m = 1 - \theta_f$.

Formulas (11) and (12) make it possible to calculate the volumetric content of fibers in two-component systems if the elastic modulus or density of the composite is previously determined. It is easy to make sure that the corresponding dependence will have the following form:

$$\theta_f = \frac{E_k - E_m}{E_f - E_m} = \frac{\rho_k - \rho_m}{\rho_f - \rho_m}$$

Relationship between mass C_f and volumetric θ_f content of fibers.

Since the two-component composite volume V_k is equal to the sum of the fibers V_f and the polymer binder V_m volumes, and the volume of each component is equal to the ratio of its mass to density, then to calculate the volumetric content of fibers we obtain the following formula

$$\theta_f = \frac{C_f}{C_f + (1 - C_f) \frac{\rho_f}{\rho_m}} = \frac{1 - C_m}{1 - C_m + C_m \frac{\rho_f}{\rho_m}}$$

Numerous experiments have confirmed that formulas (11) and (12) for nonporous unidirectional composites are in good agreement with experimental data [13].

With regard to predicting the longitudinal strength for unidirectional composites the "rule of mixtures" gives the following calculated dependence

$$\sigma_t = \sigma_f \theta_f + \sigma_m (1 - \theta_f) \quad (13)$$

where σ_t – ultimate tensile strength of the unidirectional composite; σ_f – ultimate tensile strength of fibers; σ_m – stresses in the matrix during deformation on fiber destruction; θ_f – volumetric fiber content.

In this case it is assumed to obtain the maximum strength of the fiber composite it is necessary a high content of fibers θ_f and that the destruction was happening due to the breaking of the fibers but not the matrix. The last condition is fulfilled if the volume fraction of fibers is higher than a certain minimum value approximately 0,1 [13]. As a rule, the fiber volumetric content in composite reinforcement is $\theta_f = 0,6 - 0,7$, i.e. this condition is guaranteed.

Experiments show that the calculation according to formula (13) gives overestimated values of strength in comparison with those observed in practice. Let analyze this aspect. It is known that the brittle materials strength has a significant scatter which can be described by the Weibull's distribution function [13, 24]. The strength distribution for a lot fiber can be described by this function too. As the main reason for the phenomena consideration the fluctuations of their length arising during the production of fibers, due to the scattering (within the manufacturing tolerance) of the spinneret dimensions, as well as local fluctuations the melt temperature and its rheological properties during the drawing of the fibers should be taken. All this in combination contributes to decreasing the strength of products made of unidirectional fiber composites in comparison with the theoretical strength predicted by equation (11c) for ideally laid fibers and its ideally identical properties.

So the fiber bundle strength σ_p is less than the elementary fibers average strength σ_f in general and the ratio $\eta = \sigma_p / \sigma_f$ is depend on the dispersion (spread degree) of the fibers strength also the inevitable bending of some fibers in the bundle (roving) during their production, impregnation with a polymer binder, and squeezing out excess of this binder before curing it. As a rule, brittle and bending- sensitive fibers of the carbon type have bundle strength in the range 50 – 65% of their average strength for individual fibers [13]. For somewhat less brittle glass fibers, the strength of the bundle ranges from 65% to 80% of the fibers average strength [13] and higher values are typical for bundles with a minimum properties spread and the absence of fiber bending in the bundles.

Taking into account the foregoing, when predicting the strength of unidirectional composites, it is proposed to modify the equation (11) presenting this dependence in the following form

$$\sigma_t = \eta \sigma_f \theta_f + \sigma_m (1 - \theta_f) \quad (14)$$

where η – the realizable strength factor for the fibers bundle which is equal to 0,5 ... 0,65 for carbon fibers and 0,65 ... 0,80 for glass fibers.

Matrix stresses σ_m during deformation of fiber destruction can be determined using the hypothesis of plane sections and the condition of equality the relative deformations ε of fibers and binder. From Hooke's law we can write

$$\varepsilon = \frac{\sigma_f}{E_f} = \frac{\sigma_m}{E_m}$$

Whence for stresses in the matrix (binder) we obtain

$$\sigma_m = \sigma_f \frac{E_m}{E_f}$$

Then the formula for calculating the predicted theoretical strength of the composite takes the form

$$\sigma_t = \eta \sigma_f \left[\theta_f + \frac{E_m}{E_f} (1 - \theta_f) \right] \quad (15)$$

As a rule the second term can be neglected in composite reinforcement due to the small ratio of the binder elastic modulus to the fiber elastic modulus and a calculated predictive designed estimate of the strength can be made using the following simplified formula

$$\sigma_t \approx \eta \sigma_f \theta_f \quad (16)$$

The above dependences (7), (10), (15) and (16) allow us to make a comparative structural and mechanical calculating estimate the of the coils and the of bar strength for composite reinforcement if the quantities included in these equations.

Research results and their discussion.

The available in the modern scientific and technical literature data on the construction composite reinforcement strength indexes are characterized by a significant scatter of digital values. This may be due to the discrepancy between the volumetric content of reinforcing fibers in the tested samples of the composite, differences in the composite components properties, also the imperfection of test methods [9]. The clearest evidence of such a data scatter is the dependence of the ultimate strength and elastic modulus of the composite on the diameter of the tested fiberglass (FRP) and basalt-plastic (ABP) structure reinforcement, noted in a number of experiments [1, 2]. The mechanism of this dependence has not yet been clarified in a rigorous formulation. Apparently the stress concentration effect in the reinforcement bar near the fastening half couplings has an result [9]. The

reinforcement diameter influence on the tensile strength can also be explained as follows. Composite reinforcement is a material consisting the fibers bonded with a polymeric binder the deformability of which is several times higher than that of fibers. When testing the samples, the force that squeezes the bar in the grippers is taken up by the fibers located on the surface of the bar, and then, through the binder interlayers, are transmitted to the fibers in its core.

In connection with the foregoing in this work under consideration, the predicted property indicators are determined by the lower estimate method based on the minimum values of the reinforcing fibers strength and the minimal value of the realizing factor of this strength in the beam.

Typically used for the production of fiberglass reinforcement the glass fibers of type E have the following physical and mechanical properties: density 2540 ... 2560 kg/m³; tensile elastic modulus 73 ... 77 GPa; ultimate tensile strength 3100 ... 3700 MPa [3, 25] depending on the technological features of production. Cured polyester or epoxy resins used in the production of fiberglass reinforcement depending on the grade of resin, have a density of 1100 – 1200 kg/m³ and an elastic modulus of 2.75 ... 3 GPa [3, 25]. Basalt fiber has an elastic modulus of 70 – 90 GPa and a tensile strength of 2700 – 3500 MPa [1, 2].

The shear resistance τ_s of a cured resin depend on its type, polymerization degree, type and content of hardener, also on the test method. In particular, according to [10], the shear resistance τ_s , determined by pulling out the fiberglass reinforcement bars Ø7.5 mm embedded in concrete cylinders, is 10,14 ... 10,82 MPa, depending on the thickness of the walls of the concrete cylinder. Similar results were also obtained in a number of works for composites based on carbon fibers [2]. In connection with the above, for estimated technical calculations, it is possible to take $\tau_s \approx 10$ MPa.

The crushing (compressive) strength of cured epoxy or polyester resins is 37 – 42 MPa [24]. We take for estimated calculations the average value $\sigma_b = 40$ MPa.

Since no unambiguous recommendations for the purpose for the coils braid step of the composite construction reinforcement have been developed, and the range of its change is quite wide, then for the estimated calculations we will take the height of the turn h half its width at the base, and the remaining parameters are as follows: $d/t=4$; $d/h=8$; $H/d=1$.

The experimental values of the density and mass content of the binder for a number of standard sizes of fiberglass reinforcement produced in the Republic of Belarus are shown in Table 1.

Table 1. Experimental values of density and mass content of binder in industrial fiberglass reinforcement.

Type of reinforcement	Nominal diameter, mm	Density, kg/m ³	Binder content, mass. %
AKC 6	6	2018	19,3
AKC 10	10	1980	18,63
AKC 12	12	1944	19,25

Note: the diameter of the AKC 6 reinforcement bar excluding the braiding coil is 5,2 mm, taking into account the coil is 6,2 mm.

Table 2 shows the calculated values of the predicted fiber volumetric content indexes, also the strength of the composite reinforcement and the required number of braid coils from the standpoint of ensuring equal shear and crushing strength. In the calculations, the following values of the physical and mechanical properties indexes for fibers and polymer binder were taken ($\sigma_f = 3100$ MPa; $E_f = 73$ GPa; $E_m = 3$ GPa).

Table 2. Calculated values of the binder volumetric content, predicted the composite reinforcement strength indexes and the required number of braid coils from the standpoint of ensuring equal strength with the bar.

Type of reinforcement	Calculated volumetric content of binder, %	Predicted minimal strength, MPa	Calculated number of coils from the point of view of ensuring equal strength with the bar	
			for shear	for crush
AKC 6	66,2	1361	130	65
AKC 10	67,2	1354	129	64
AKC 12	66,3	1364	130	65

The analysis shows that the calculated estimate values of the minimal predicted strength 1354 – 1364 MPa are in good agreement with those specified in the STB 1103-98 "Fiberglass reinforcement" standard (taking into account the amendments). The standard stipulates ultimate strength σ_c for bars with a diameter of 6 mm is at least 1300 MPa and a standard resistance R_n is at least 1200 MPa. This indexes are at the correctness for the application of the modified notation of Eq. (14) to predict the longitudinal strength of unidirectional composites.

From the values presented in Table 2, it can be seen that the coils of the reinforcement braid work for shear and crush not efficiently and provide mainly technological strength, preventing the bar from delamination at the stage of reinforcement manufacturing. It is advisable for increasing the efficiency to make in accordance with the accumulated experience, a rough surface with the application of silicate particles, which contribute to strengthening the setting of concrete with the surface of the reinforcement (Fig. 2.)



Fig. 2. Samples of composite construction reinforcement with a layer of mineral particles applied to the surface.

In this case, the step of the braid does not have a determining value and can be assigned from the conditions of the convenience of winding, i.e. may be large in comparison with the one assumed in the calculations in this article.

Conclusion.

It is made a calculating estimate the conditions for ensuring the uniform strength of rupture and braid coils of construction composite reinforcement bar for shear and crushing. Theoretically substantiated the assumption of a relatively low loading capacity of the braid coils in comparison with the loading capacity of the reinforcement bar. The results obtained can be used by manufacturers and consumers of construction composite reinforcement, also in the educational process at the training of engineering personnel for the construction profile.

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