Determination of the strength of the support sections of concrete beams with BFRP under the action of shear forces

I Karpiuk1,*, Ye Klymenko1, V Karpiuk1, A Posternak1, O Maistrenko1 and A Tselikova1

1Odessa State Academy of Civil Engineering and Architecture, 4 Didrihson Street, 65029, Odesa, Ukraine

*E-mail: irina.carpyuk@gmail.com

Abstract. In a few foreign codes (ACI, Eurocode 2, JSCE, CSA, CNR), the principles for calculating flexible concrete elements with (BFRP) are preserved the same as for calculating concrete structures with steel reinforcement. Experimental studies have not confirmed these principles, which indicates the relevance of research. Two calculation models are proposed for determining the strength near the support sections of concrete beams with BFRP. The first model considers the calculation of beams with average \((a/d=2)\) and large \((a/d=3)\) shear spans along the main inclined crack, taking into account the experimentally established length of its projection \(l_{crf1}\), the coefficients \(\phi_{c2}\), \(\phi_{c3}\) and \(\phi_{c4}\) the magnitude of tensile stresses in the transverse fittings. The second computational model provides for the calculation of these beams with small shear spans \((a/d\leq1)\) along a compressed inclined strip using the experimentally established coefficient \(k_f\). The use of the presented design models provides good convergence (coefficient of variation \(\nu=8\%\)) of the calculated and experimental values of strength near the support sections of concrete beams with BFRP.

1. Introduction

Recently, concrete structures with non-metallic composite reinforcement (FRP) are increasingly used in the construction of bridge spans, in hydraulic and transport construction, in the arrangement of treatment facilities, chemical and food industry facilities, as well as special-purpose buildings. The advantages of using basalt-plastic reinforcement (BFRP) are the low cost of the main raw material (basalt fibers), due to the large reserves in the world of basalt, as well as their unique physicochemical and mechanical properties.

High strength, resistance to chemical and physical corrosion, dielectric and dimagnetic properties, low weight and low thermal conductivity of FRP contribute to its increasing use instead of steel reinforcement. However, the widespread use of FRP for reinforcing concrete structures is complicated by the insufficient number of studies carried out on this topic, as well as experimentally confirmed author's and normative methods for calculating their bearing capacity. And if there are relatively many publications devoted to the calculation of the strength of normal sections of elements with FRP, then the question of determining the bearing capacity of their inclined sections is still open. The existing theory of calculating structures reinforced with non-metallic composite reinforcement is based not on experimentally substantiated design schemes, but on various kinds of analogies. Therefore, research in this area is important and relevant.

2. Analysis of recent publications

In the Odessa State Academy of Civil Engineering and Architecture, complex experimental and theoretical studies of the bearing capacity of concrete beam elements with BFRP are carried out [1, 2]. Comparison [3] of the obtained experimental data [1, 2] of the bearing capacity of inclined sections of the indicated structures with the results of calculations according to the recommendations of the European EUROCODE-2 [4], Japanese JSCE [5], American ACI [6], Canadian CSA [7], Italian CNR [8] design codes, showed significant discrepancies between them (variation coefficients \(\nu\) fluctuate...
within 59-85%). These norms, as a rule, underestimate their real bearing capacity by several times. The poor convergence of experimental data with the results of calculations is due to the fact that these norms are based not on real physical schemes of the operation of such structures, but on the classical (more than a century old) model of the truss analogy W. Ritter - E. Mörch and its various modifications, arched analogy or a combination of truss and arched analogies. A remarkably good convergence ($\nu = 17.5\%$) of experimental data and calculation results was shown by A.A. Gvozdev, A.S. Zalesova, A.F. Ilyin et al. As amended by SNiP [9] for beams reinforced with steel reinforcement [10]. Obviously, this method is advisable to adapt and apply to the design of concrete beams with FRP.

The aim of this work is to improve the existing design models based on the method of limiting forces, bearing capacity of inclined sections of concrete beam structures with FRP.

Research methods. Before the start of laboratory experiments, predictions were made for assessing the bearing capacity of prototypes-beams by modeling their stress-strain state in the PC "Lira - SAPR". Experimental samples - the beams were reinforced with basalt-plastic reinforcement BFRP and manufactured in accordance with the planning theory according to the three-factor, three-level Box-Behnken B3 plan. The beams were tested according to a four-point scheme under a static effect of a load, which was applied in steps of up to $0.1F_{ult}$. The load holding at each stage was 15 minutes with taking readings from measuring instruments, measuring the width of the opening of normal and oblique cracks. The experimental data of the bearing capacity of the beams were compared with the results of calculations according to the recommendations of the existing national design standards and author's methods. For further improvement, the method of limiting efforts was chosen, which turned out to be the closest to the physical picture of the work of concrete beams with FRP.

3. Main material and results

The performed comparisons [3, 9, 11] of the experimental and calculated values of the bearing capacity of the inclined sections of the experimental concrete beams with steel reinforcement showed their unsatisfactory, in general, convergence. The coefficients of variation $\nu$ vary from 17.5% (the method of limiting efforts by A. A. Gvozdev, A. S. Zalesov, A. F. Ilyin as amended by SNiP 2.03.01-84*) to 65.4% (Eurocode - 2). These discrepancies are presented [3] also in graphical form, in the form of the influence of the most significant design factors on the bearing capacity of inclined sections of reinforced concrete beams. Thus, the method of limiting efforts, laid down in the previously existing SNiP [9] and based on the experimentally provided physical picture of the operation of reinforced concrete beam structures, is in better agreement with the available experimental data (ASD series) [10, 12] than the European standards EN [4], which are based on a modified truss analogy.

Experimental data [1, 2, 3] on the study of the bearing capacity of concrete beams, reinforced with BFRP, also do not agree with the results of calculations according to foreign design standards. The coefficients of variation $\nu$ range from 59.0% (CNR) to 85.2% (EN). Especially inadequately they reflect the influence of the relative shear span $a/d$. Thus, a comparison of the experimental and calculated values of the bearing capacity of concrete beams with BFRP showed that a modified truss analogy or a modified theory of compression fields cannot serve as adequate design schemes for determining the strength of their inclined sections.

4. Features of the calculation of the bearing capacity of inclined sections of concrete beams with basalt-plastic reinforcement

Taking into account the recommendations of A. A. Gvozdev, A. S. Zalesova, A. F. Ilyin as amended by SNiP [9], calculation of concrete beams with large ($a/d=2$) shear spans, reinforced in sufficient quantity ($\rho_v \geq 0.0025$, $\rho_f \geq 0.0100$) with basalt-plastic reinforcement BFRP (Figure 1), on the combined action of shear force and bending moment to ensure their bearing capacity along an inclined crack is recommended to be carried out along the most dangerous inclined section from the condition:

$$V_f \leq V_{fs} + V_{fs} + V_{j,inc}.$$  (1)
Figure 1. Scheme, near the support section of a concrete beam, reinforced with BFRP, when determining the bearing capacity of its inclined section.

Where $V_{fc}, V_{fu}, V_{f,inc}$ are the components of the shear force, which are perceived, respectively, by concrete, transverse basalt-plastic reinforcement and bends.

The transverse force $V_f$ in condition (1) is determined from the external load located on one side of the inclined section under consideration.

The component of the shear force perceived by the concrete in the compressed zone is proposed to be determined using the improved formula of A.S. Zalesova and A.F. Ilyina:

$$V_f = \varphi_{c2}(1 + \varphi_f + \varphi_{fu}) f_{cat} \cdot b_w \cdot d^2 / a,$$

where $a = c$ is the length of the projection of the most dangerous inclined section on the longitudinal axis of the element (span of the cut);

$\varphi_{c2}$ - coefficient that comprehensively takes into account the influence of the shear span, the concrete class and the amount of transverse reinforcement BFRP. This coefficient, in contrast to its prototype $\varphi_v=2$ in SNiP [9] for heavy concrete, takes into account the influence of design factors on the value of $V_f$, in a differentiated manner. The $\varphi_{c2}$ coefficient was obtained experimentally. Having experimentally established adequate values of the projection length of a dangerous inclined crack $l_{crf} = L_0$ (experimental-statistical dependence (3), as well as confirmed by direct measurements of deformation $\varepsilon_{fu}$ and modeling of SSS stress $\sigma_{fu}$ in transverse reinforcement bars, reliable values of the components $V_{fu}$ were determined.

Hence the experimental significance $V_{fc} = V_f^{exp} - V_{fu}$. At the same time $V_{f,inc} = 0$, since there were no bends in the beams.

The length of the projection of a dangerous inclined crack can be represented by the following experimental-statistical dependence:

$$\hat{Y}(l_{crf}) = 176 + 25X_1 + 9X_2 - 16X_3 - 9X_4^2 + 8X_5^2 - 9X_6^2 - 9X_7X_8, MM \cdot \sigma = 5.4\%.$$

The experimental-statistical dependence of the variable coefficient $\varphi_{c2}$ has the form

$$\hat{Y}(\varphi_{c2}) = 1.38 - 0.25X_1 - 0.12X_2 - 0.22X_3, MM \cdot \sigma = 5.2\%,$$

which, after replacing the coded variables with natural values of design factors, turns into the following form:
\[ \varphi_{c2} = 1.38 - 0.25 \left( \frac{a}{h_0} - 2 \right) - 0.12 \left( \frac{C - 35MIIa}{15MIIa} \right) - 0.22 \left( \frac{a}{h_0} - 2 \right) \left( \frac{\rho_{fu} - 0.0072}{0.0043} \right). \] (5)

Taking into account the admissible extrapolation of the obtained results, dependence (5) is valid for the following values of design factors:
- the relative span of the cut (factor \( X_i \)), \( a/d = 1.0-3.3 \);
- concrete class \((X_2)\) in MPa from C12 / 15 to C45 / 55;
- transverse reinforcement coefficient \((X_3)\) \( \rho_{fu} = 0.0018-0.0126 \).

For practical use, the length of the projection of a dangerous inclined crack in concrete beams with FRP, including BFRP, under static load action, is recommended to be determined by the experimental-statistical dependence (3), which, after replacing the coded variables with their natural values, takes the form:

\[ l'_{cfr} = 176 + 25(a / h_0 - 2) + 9 \left( \frac{C - 35MIIa}{15MIIa} \right) - 16 \left( \frac{\rho_{fu} - 0.0072}{0.0043} \right) - 9(a / h_0 - 2)^2 + 8 \left( \frac{C - 35MIIa}{15MIIa} \right)^2 - 9(a / h_0 - 2) \left( \frac{\rho_{fu} - 0.0072}{0.0043} \right)^2 \] (6)

Obviously, dependence (6) is also valid when the design factors change within the same limits as in expression (5).

The forces perceived by transverse reinforcement are traditionally determined by the formula (7):

\[ V_{ju} = q_{ju} \cdot l'_{cfr}, \] (7)

where \( q_{ju} \) is the intensity of the transverse reinforcement or the force in the transverse rods (clamps) per unit length of the beam, determined by the formula (8):

\[ q_{ju} = \sigma_{ju} \cdot \frac{A_{ju}}{S}, \] (8)

where \( \sigma_{ju} \) - stresses in the rods of transverse non-metallic composite reinforcement, which are crossed by a dangerous inclined crack.

Based on the results of in-situ measurements of deformations, as well as by modeling the stress-strain state, it was found that the stresses in the transverse bars BFRP, in beam structures with large shear spans \( a/d = 3 \), are \( 0.10f_{ck} \), and in beams with average shear spans \( a/d = 2 \) \( \sigma_{ju} = 0.15f_{ck} \). In this case, the relative deformations \( \varepsilon_{fw} \) in them before the destruction of the experimental specimens - beams were, respectively, 0.0018 and 0.0028. These data are in good agreement with the fib recommendations [14, 15, 16] to limit the relative deformations of transverse nonmetallic reinforcement to 0.20-0.25%.

In experimental beams with small shear spans \( a/d \leq 1 \), direct measurements and modeling of stress-strain state showed that in vertical transverse bars BFRP compressive stresses reached, on average, \( -363MIIa \simeq -0.45f_{ck} \), and relative deformations \( \varepsilon_{fw} \simeq -0.0084 \). It is obvious that the probability of destruction near the support sections of such elements from a cut of concrete along an inclined crack \( (max\sigma_{ez} \leq f_{ck}/2) \) or along an inclined compressed strip \( (max\sigma_{ez} = (1.0-1.5) f_{ck}) \) is the same. However, given that the height of the compressed concrete zone above the top of a dangerous inclined crack under a concentrated force applied at the end of the shear span is artificially reduced (by 25% or more) due to shear deformations in concrete, the probability of its destruction according to the design scheme (Figure 1), nevertheless, remains with concrete shear and without taking into account the work of transverse reinforcement \( (\sigma_{ju} = 0) \).

Let us check such a possibility of destruction near the support sections of beams with small shear spans a little lower.

Shear force perceived by the bends:
When determining \( q_{fw,inc} \) it is necessary to take into account the angles of inclination \( \alpha \) and it is allowed to take stresses in them \( \sigma_f = 0.25f_{ck} \) with \( \varepsilon_{f,inc} = 0.0045 \) according to the fib recommendations [14, 15, 16] and under the condition of reliable anchors (bends) on the supports and in the spans of structures.

In beam structures with large and medium shear spans, in which non-metallic composite transverse reinforcement is installed according to calculation, the following condition must be met:

\[
q_{fw} \geq \frac{\varphi_{c3}(1 + \varphi_f + \varphi_{\alpha}) \cdot f_{cd} \cdot b}{2},
\]

as well as the corresponding design requirements.

Calculation of concrete beams reinforced only with longitudinal non-metallic composite reinforcement (without transverse rods and clamps) for the combined action of shear forces and bending moments in order to ensure their bearing capacity along an inclined crack is also recommended to be performed along the most dangerous section from the condition:

\[
V_f = \frac{\varphi_{c3}(1 + \varphi_f) f_{cd} b \cdot d^2}{\alpha'},
\]

in which, the right-hand side should not exceed the value and should not be less

\[
\varphi_{c3}(1 + \varphi_f) f_{cd} b \cdot d.
\]

It is recommended to determine the \( \varphi_{c3} \) coefficients taking into account their decrease in comparison with the \( \varphi_{b3} \) coefficients from SNiP [9] according to the formulas:

\[
\varphi_{c3} = \frac{\varphi_{c2}}{\varphi_{b2}}, \quad \varphi_{c4} = \frac{\varphi_{c3}}{\varphi_{b2}} \varphi_{b4},
\]

Moreover, for heavy concrete \( \varphi_{b3} = 0.6 \) and \( \varphi_{b4} = 1.5 \).

Comparison of experimental data and calculated values of bearing capacity of inclined sections of concrete beams with BFRP performed in [3] according to the method of limiting forces improved for FRP showed, in general, their satisfactory convergence (\( v = 11\% \)). The largest discrepancies between the experimental and calculated values of the breaking shear force were observed in basalt concrete beams with small shear spans (\( a \leq d \)). To improve the convergence of the experimental and predicted values of the bearing capacity near the support sections of concrete beams with BFRP with small shear spans (\( a \leq d \)), we calculate it, according to the recommendations of T.I. Baranova [17], according to the scheme of short cantilevers, transformed in our case to the form (Figure 2). The validity of this approach is confirmed by the results of field experiments using distribution plates of width \( l_{sup} \) under concentrated forces and on supports, as a result of which an artificial reduction in the cut span occurred. This conclusion is also confirmed by the results of modeling the stress-strain state of concrete and transverse reinforcement, which in all beams with such shear spans experienced compression defloration.
The bearing capacity of the inclined compressed strip of the considered beam is determined from the condition:

\[ V_f \approx F \leq k_f \cdot \varphi_{w2} \cdot f_{cd} \cdot b \cdot l_c \cdot \sin \theta \leq 3.5 f_{cd} \cdot b \cdot h_s, \]
\[ k_f \cdot \varphi_{w2} \cdot f_{cd} \cdot b \cdot l_c \cdot \sin \theta \geq \frac{\varphi_{w1} (1 + \varphi_{w1}) f_{cd} \cdot b \cdot d^2}{a}, \]

where \( \theta \) is the angle of inclination of the compressed strip on the support section of the beam to its longitudinal axis;

\( l_c \) - the width of the calculated compressed strip, which is determined by the formula:

\[ l_c = l_{sup} \cdot \sin \theta, \]

where \( l_{sup} \) is the length of the load transfer area along the beam span;

\( \varphi_{w2} \) - coefficient, taking into account the influence of the horizontal or inclined strips, located at the height of the beam along the normal to them. In this case, only horizontal strips or those inclined at an angle of not more than 45° to the horizontal are taken into account in compliance with the relevant design requirements.

Instead of the coefficient \( k_f \), when calculating short cantilevers according to the method [17], its constant value equal to 0.8 is used. For concrete beams with a small shear span and short cantilevers reinforced with BFRP, inversely recalculated, the experimental values of the coefficient \( k_f \) were found by the formula

\[ k_f = \frac{V_{af}}{\varphi_{w2} \cdot f_{ck} \cdot b \cdot l_c \cdot \sin \theta}, \]

subject to conditions (14).

The processing of the values of the coefficient \( k_f \) obtained in this way using the least squares method made it possible to obtain an adequate experimental-statistical dependence for the indicated concrete beams or short cantilevers.
\[ Y(k_f) = 1.67 - 0.25X_2 - 0.21X_3 - 0.08X_2X_3, \quad \nu = 2.5\% , \quad (18) \]

replacing the coded variables with natural values of design factors, within the framework of the carried out full-scale experiment, made it possible to obtain an empirical expression for the coefficient \( k_f \), which is fair taking into account the permissible extrapolation outside the limits of the concrete class change from C12/15 to C45/55 and the coefficient of transverse reinforcement, \( \rho_{bw} \) from 0.0018 to 0.0126:

\[ k_f = 1.67 - 0.25\left( \frac{C - 35MPa}{15MPa} \right) - 0.21\left( \frac{\rho_{bw} - 0.0072}{0.0043} \right) - 0.08\left( \frac{C - 35MPa}{15MPa} \right)\left( \frac{\rho_{bw} - 0.0072}{0.0043} \right) . \quad (19) \]

The geometric interpretation of the dependence of the coefficient \( k_f \) on the ratio of design factors is shown in Figure 3.

**Figure 3.** Influence of the class of concrete and the amount of transverse reinforcement on the value of the variable coefficient in condition (14).

Thus, the use of experimentally established coefficients for beams reinforced with BFRP, with large \((a/d=3)\), medium \((a/d=2)\), as well as \( k_f \) for elements with small \((a/d\leq1)\) shear spans, allowed to bring together the experimental and calculated values of their bearing capacity near the reference sections, to a satisfactory convergence \((\nu=7.9\%)\).

The design of concrete T-beams and I-beams reinforced with BFRP, with the combined action of a shear force and a bending moment, is performed to ensure the strength of the inclined strips between the inclined cracks in their walls in the vicinity of the support sections according to the formula:

\[ V_f \approx F \leq 0.3\varphi_{a1} \cdot \varphi_{cd} \cdot f_{cd} \cdot b_w \cdot d , \quad (20) \]

where \( V_f \) - coefficient that takes into account the effect of transverse bars or stirrups normal to the longitudinal axis on the bearing capacity near the support sections of these beams. It is recommended to determine it by formula (16) and take equal to no more than 1.1;

\( b_w \) - wall thickness of T-section or I-section.

The coefficient \( \varphi_{a1} \) is recommended to be determined by the method of A. S. Zalesova and A. F. Ilyin, stated in [9], with the adjusted value of the coefficient \( \beta^r \):

\[ \varphi_{a1} = 1 - \beta^r \cdot f_{cd} , \quad (21) \]

where \( \beta^r = (\varphi_{c2}/\varphi_{b2})\beta \),
\( \varphi_{b2} \) and \( \beta \) - experimental values of the coefficients from [9]. For heavy concrete, their values are, respectively, 2 и 0.01.
5. Conclusions:

1. Comparison of the experimental values of the bearing capacity of inclined sections of concrete beams reinforced with BFRP with the results of calculations performed in accordance with the recommendations of the existing national design codes of foreign countries [3] showed unsatisfactory convergence: the coefficient of variation \( \nu \) using Eurocode-2 [5] was 85.2\%, Japanese JSCE [5] 77.9\%, American ACI [6] 81.7\%, Canadian CSA [7] 61.1\%, Italian CNR [8] 59\%. Basically, these norms significantly underestimate the real bearing capacity near the supporting sections of the experimental samples - beams. Based on the foregoing, the basic principles on which the considered national standards for the design of concrete structures with FRP are based cannot be adopted for calculating the bearing capacity of the considered sections of beams reinforced with BFRP, without making appropriate changes and adjustments to them.

2. In order to search for the closest to reality physical models of the operation of experimental reinforced concrete beams (series 1, ACD), which are analogs of concrete beams reinforced with BFRP, a comparative analysis of the data (their actual bearing capacity with its calculated values) was made, which was determined by the method boundary efforts [9], as well as using a modified truss analogy [4, 13]. It was found that the method of boundary forces [9] provides a significantly better convergence (\( \nu = 17.5\% \)) of the experimental and calculated values of the bearing capacity of concrete beams with steel reinforcement in comparison with the modified truss analogy [4, 13] (\( \nu = 65.4\% \)). This method is better than European and others, as studies have shown [10, 11], design standards reflect the physical picture of the work of the investigated beams under load.

3. Considering the above, the bearing capacity of inclined sections of concrete beams reinforced with BFRP is recommended to be determined by the method of boundary forces. At the same time, the calculation of beams with large \( (a / d = 5) \) and medium \( (a / d = 2) \) shear spans should be performed along an inclined crack using variable coefficients \( \varphi_{e2}, \varphi_{e3}, \varphi_{e4} \), taking into account the real projection length of a dangerous inclined crack \( l'_{crf} \) and a significant reduction in tensile stresses \( \sigma_{fw} \) to \((0.10 - 0.15)f_{\mu}\) in transverse reinforcement. The bearing capacity near the support sections with small \( (a \leq d) \) shear spans must be determined as for short cantilevers along an inclined compressed strip between the concentrated force and the support using a variable coefficient \( k_f \).

Compliance with these requirements allows for satisfactory convergence of the calculated and experimental values of the bearing capacity of inclined sections and near the support sections of concrete beams reinforced with BFRP, to carry out their reliable and, at the same time, more economical design.

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