The use of FRP of increased thickness for strengthening structures

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Abstract. The external reinforcement system based on carbon fiber has been used for decades to strengthen reinforced concrete elements. At the same time, it is impossible not to recognize that the existing calculation methods are largely based on empirical dependencies obtained from experimental studies. One of these issues is related to the application of the methodology for materials of heterogeneous origin-tapes and laminates. In general, the possibility of applying the calculation methods accepted in the norms for laminates of generally accepted thicknesses up to 1.6 mm is determined. The question related to the possibility of using laminates of greater thickness is not sufficiently studied. This article deals with the calculation of the reinforcement of the normal cross sections of the bent reinforced concrete elements with the reinforcement of laminates with a thickness of 5 mm.

1 Status of the issue (according to the methods accepted in the national codes)

The calculated positions for determining the load-bearing capacity of the normal cross-sections of the bent elements reinforced by external reinforcement include a number of empirical dependencies [1-21]. At the same time, these methods involve the calculation of various materials that have fundamentally different properties (fabrics and lamellas). Calculations of massively applied lamellae with a thickness of up to 1.6 mm show a convergence with the results of experimental data of up to 30%. Now a number of manufacturers have launched a series of lamellas with a thickness of up to 5 mm. There are data on the results of experimental studies, but there is no analysis of the applicability of existing calculation methods for external reinforcement systems of this thickness.
В качестве рассматриваемых методик расчета будут рассмотрены:
- the methodology described in [1-4] with the appropriate justification and analysis materials based on this methodology;
- methodology of Russian regulatory documents-SP 164.1325800 with justification [6, 7].

In general, the method [1] is represented by the following algorithm:
- determination of the properties of materials depending on the material and the placement of the structure (assignment of the reliability coefficient for the material);- determination the existing state of strain

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- determination of the calculated deformations of the external reinforcement (1)

$$\varepsilon_{fd} = 0.41\sqrt{\frac{R_b}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \quad (1)$$

- determination of the calculated value of the deformations of the external reinforcement, taking into account the deformations of concrete (steel reinforcement) according to the equation (2)

$$\varepsilon_{fe} = 0.003\left(\frac{d_f - c}{c}\right) - \varepsilon_{bt} \leq \varepsilon_{fd} \quad (2)$$

- determination of the design stress in the external reinforcement based on the design deformations of the steel reinforcement according to the equation (3)

$$R_{fe} = E_f \varepsilon_{fe} \quad (3)$$

- further calculation of the bending moments perceived by the cross-section with reinforcement, while also monitoring the stresses in the steel reinforcement and external reinforcement

Notification:

R_b – compressive stress in concrete, MPa;

E_f – tensile modulus of elasticity of FRP, MPa;

t_f – nominal thickness of one ply of FRP reinforcement, mm;

ε_{fu} – degign rupture strain of FRP reinforcement;

ε_{fe} – effective dtrain in FRP reinforcement attained in failure;

d_f – effective depth of FRP flexural reinforcement, mm;

c – distance from extreme compression fiber to neutral axis, mm;

ε_{bt} – strain in the concrete.

In general, a similar algorithm is used in the methods [6, 7]:

- determination of the calculated resistance of the external reinforcement by the formulas:

$$R_f = \frac{\gamma_{f1} \cdot \gamma_{f2} \cdot R_{f,n}}{\gamma_f} \quad (4)$$

$$\gamma_{f2} = \frac{1}{2{,}5\varepsilon_{fu}}\sqrt{\frac{R_b}{nE_f t_f}} \quad (5)$$

- determination of deformations of external reinforcement, steel reinforcement and concrete, taking into account the possible formation of cracks:

$$\varepsilon_s^0 = \frac{M_0}{E_{b1} I_{red}}(h_0 - x_0) \quad (6)$$

$$\varepsilon_b^0 = \frac{M_0}{E_{b1} I_{red}} x_0 \quad (7)$$

- adjustment of the strength of the external reinforcement

$$R_f < (\varepsilon_{s2} - \varepsilon_s^0) E_f \quad (8)$$

2 Analysis of calculation methods

In general, analyzing these methods, we can conclude that in most cases, the determining formula is (1) and the analog (4, 5). Restrictions on formulas (2, 6-8) affect the value of the strength of the external reinforcement in a limited number of cases.

At the same time, the following provisions can be distinguished:

- method [1] the defining function is equation (1), which is used to determine the calculated strength of the external reinforcement:

$$R_{fe} = E_f \varepsilon_{fe} = E_f \cdot 0.41\sqrt{\frac{R_f}{nE_f t_f}} = 0.41\sqrt{\frac{R_f E_f}{nt_f}}$$

- the method [6, 7] is reduced to a similar defining formula:

$$R_f = \frac{\gamma_{f1}\gamma_{f2}R_{f,n}}{\gamma_f} = \frac{\gamma_{f1}\cdot\frac{1}{2.5\varepsilon_{f,ult}}\sqrt{\frac{R_b}{nE_f t_f}}\cdot R_{f,n}}{\gamma_f} = \frac{\gamma_{f1}\cdot\frac{1}{2.5\frac{R_f}{E_f}}\sqrt{\frac{R_b}{nE_f t_f}}\cdot R_{f,n}}{\gamma_f}$$

$$= \frac{\gamma_{f1}\cdot\frac{E_f}{2.5\frac{\gamma_{f1}\cdot 1.0\cdot R_{f,n}}{\gamma_f}}\sqrt{\frac{R_b}{nE_f t_f}}\cdot R_{f,n}}{\gamma_f}$$

$$= \frac{\cancel{\gamma_{f1}}\cdot\frac{E_f\cancel{\gamma_f}}{\cancel{2.5\,\gamma_{f1}}\cdot 1.0\cancel{\cdot R_{f,n}}}\sqrt{\frac{R_b}{nE_f t_f}}\cdot\cancel{R_{f,n}}}{\cancel{\gamma_f}} = \frac{E_f}{2.5}\sqrt{\frac{R_b}{nE_f t_f}} = \frac{1}{2.5}\sqrt{\frac{E_f R_b}{nt_f}}$$

2.1 The dependence thickness/effective stress in FRP

By analyzing the resulting dependencies, you can plot the dependence of the strength of the external reinforcement on the thickness of the external reinforcement. In this case, the thickness of the external reinforcement should be understood as the total thickness $t=nt_f$.

The graph is shown in **Fig. 1** for the base materials concrete B15, B25 and B35 and the elastic modulus of the external reinforcement 245,000 MPa.

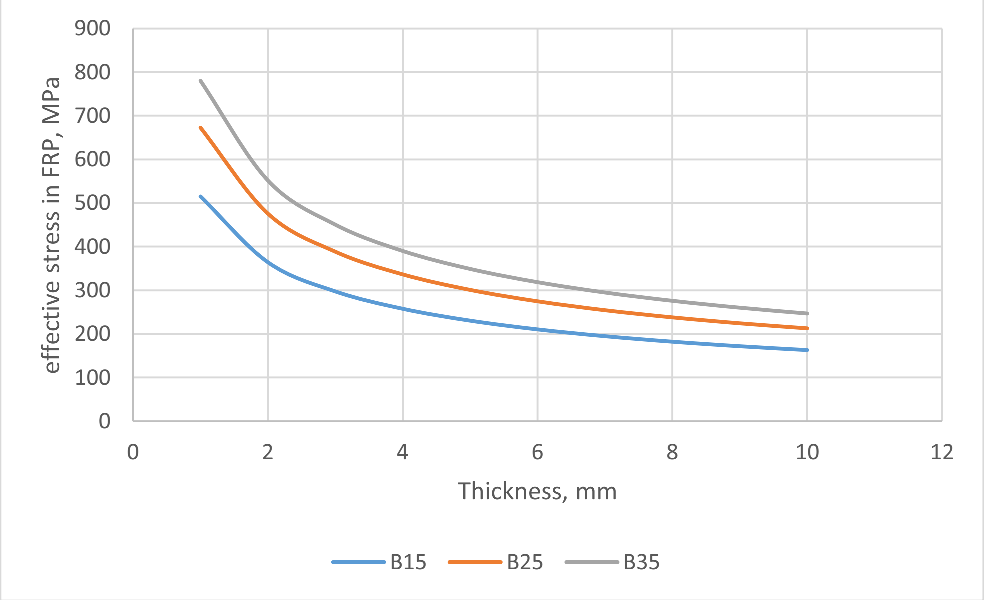

Fig. 1. Dependence thickness/effective stress in FRP.

Figure 2 shows the dependence of the longitudinal force of the external reinforcement on the thickness. In particular, the value for steel reinforcement with a diameter of 12 mm and a strength of 345 MPa is given for comparison.

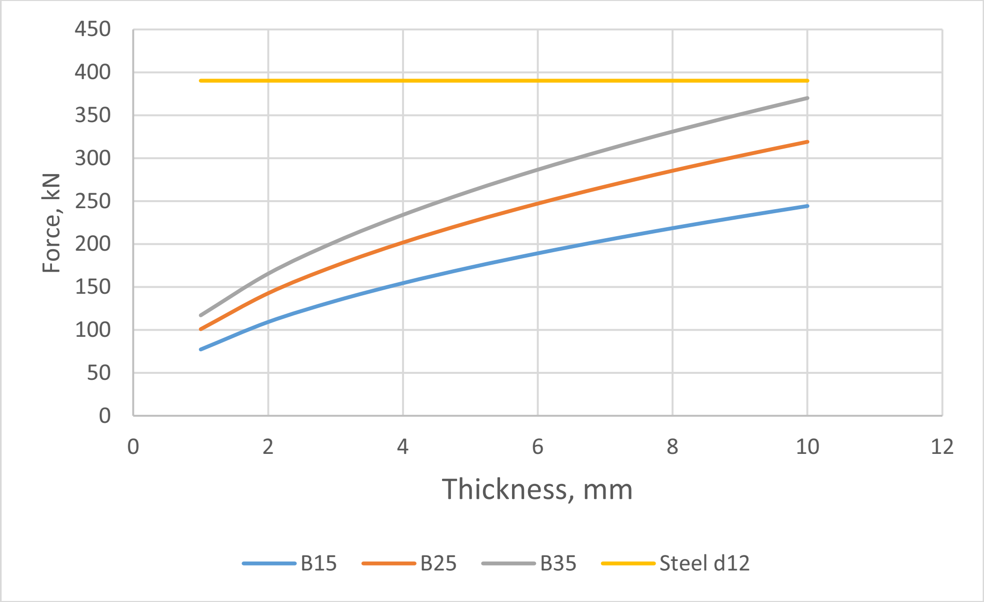

Fig. 2. Dependence thickness/effective stress in FRP.

As you can see from these graphs, a significant decrease in the effectiveness of external reinforcement based on carbon fibers is observed up to a thickness of 2.0 mm. Further reduction in efficiency of a smaller order.

At the same time, the presented data are calculated according to the methods [1,6,7] and differ significantly from the experimental data presented below.

3 Comparison with real experiments

For the analysis of the theoretical positions, the results of testing single-span beams with reinforcement of the lower zone with carbon fiber lamellas were accepted.

The general test and reinforcement scheme is shown in Figure 3.

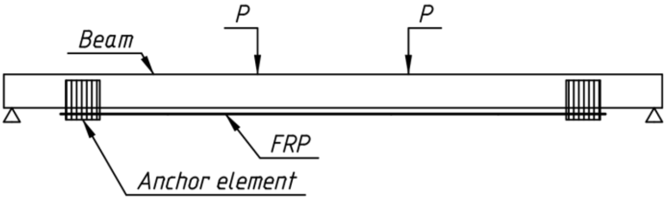

Fig. 3. Settlement scheme (the scheme of the experiment)

The type of reinforcement with high-thickness lamellae is shown in Fig. 4

Fig. 4. Type of pasted composite

According to the results of the tests, as well as the comparative calculation, the data on the load-bearing capacity were obtained, presented in Table 1.

Table 1. Load-bearing capacity of the beam according to experimental studies and calculations

gain	Load-bearing capacity, bending moment, M, kN*m		
	Experiment	calculation by [1]	calculation by [6, 7]
Lamel 1,2 mm	**54,7**	41,0	49.5
Lamel 5.0 mm	**65,11**	33,9	36.4
	64,73	33,9	36,4

By comparing the results obtained, you can evaluate the discrepancy in the calculation methods:
- for thin slats, the difference is 9.5% [6, 7] and 25% [1];
- for lamellae with a thickness of 5 mm, the discrepancy is 48% [6, 7] and 44% [1].

These results confirm the empirical nature of the methods [1, 6, 7].

4 Conclusions

Based on the results of the work performed, the following conclusions can be drawn:
1. The available methods for calculating the load-bearing capacity of externally reinforced bendable elements are largely based on empirical dependencies.
2. The accepted empirical dependences are mainly focused on "thin" gain elements, for which the convergence with numerical calculations is 25%. For "thick" gain elements, the difference between the calculated data and the experimental results is more than 40%.
3. Also, the existing calculation methods do not take into account many factors that affect the final value of the load-bearing capacity:

- anchoring of external reinforcement;
- the average strength of the element is taken into account in the calculations, at the same time, the need to take into account the surface strength in the attachment zone of the external reinforcement is proved;
- parameters of the binder (adhesion to the concrete surface, adhesion between the fibers - according to the thickness of the composite, etc.).

4. In general, it can be concluded about the effectiveness of 5.0 mm thick lamellas according to field tests. When adjusting the calculation method, a reasonable rational application for strengthening structures is possible.

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