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Review Article

EVALUATING THE EFFECTIVENESS OF TECHNICAL SOLUTIONS FOR REINFORCING CONCRETE STRUCTURES WITH COMPOSITE MATERIALS

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Abstract
In recent years, the problems of ensuring the durability and operational reliability of structures have attracted the attention of many experts, and calculations of structures for durability are becoming the norm in many countries of the world.
In industrialized countries, more than 40% of all investment in the construction industry is used for maintenance and repair of reinforced concrete structures. At the end of the last century, in the United States, more than $ 20 billion a year was required to repair bridges made of reinforced concrete, and according to calculations, these costs have increased by more than $ 0.5 billion annually. In the UK, more than $ 1 billion is spent annually on repairs of such structures, and there is a tendency to increase operating costs. In Russia, the funds spent on the repair and restoration of individual industrial structures for 4-5 years have reached an amount equal to their total cost.
Examination of the experience of operating engineering structures made of concrete and reinforced concrete shows that they are destroyed much earlier than should be according to the design standard period due to accelerated physical wear. The costs of repair and restoration of structures are significantly higher than planned, and the timing of their implementation, the volume and content of work are assigned without taking into account the current and future state of the structural elements.
Repair and restoration of the reinforced concrete structures currently, unfortunately, do not have a coherent and deep scientific basis to assess their
effectiveness. Today, according to experts, the condition of most repaired structures made of reinforced concrete is noticeably deteriorating several years after they have been repaired. According to
research, about 75% of failures in the repair of the reinforced concrete structures will occur in 5 years of operation only. It is considered to be a success if repeated repairs must be performed in 12-15 years, and in the ideal case, such work must be repeated in 25 years. The punctuality of the work is due to significant amounts of work on the reconstruction, repair and strengthening of buildings and structures, including historical monuments and architectural monuments, and the resulting problem of rational and reliable design of strengthening structures using composite materials based on carbon and glass fibers.
The purpose of this work is to examine the parameters and indicators for evaluating the effectiveness of technical solutions for reinforcing the concrete structures with composite materials.
Examination and determination of the requirements of normative and technical documentation for composite materials, formation of criteria for evaluating the effectiveness of the reinforced concrete structures with composite materials, determination of significance coefficients for criteria for evaluating the effectiveness of reinforced concrete structures with composite materials.

Key Words: reinforcement, manufacturability, efficiency, composite materials, reinforced concrete structures, significance factors.

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INTRODUCTION
Composite materials under tension have a linear relationship between deformations and stresses before failure. The number, type, and orientation of the reinforced fibers determine the properties of these materials.

THEORETICAL FRAMEWORK
There are several ways of strengthening of flexible reinforced concrete with the help of CM, which can be classified as follows:
1. Wetlayup (handlayup) system. This method involves the use of canvas woven materials for strengthening, which act as a reinforcing filler for CM. Before laying the first layer of reinforcing material, the surface of the reinforced structure is covered with a binder. Next, the reinforcing material is placed, which is melted into the polymer matrix. For multi-layer installation, each subsequent layer is further impregnated with a binder after being applied on top.
The reinforcing material can be impregnated with a binder before being placed on the concrete surface in a separate process, even with the use of an impregnating machine. The binder is cured in a "cold state".
2. The use of molded and cured in the factory of products from structural steel to amplify (Precured system). In this method, ready-made composite products are used for strengthening, which are glued to the surface using a binder. Finished composite products are lamellas, flat sheets, grids, corners, clips, and shirts. Lamellas are the most widely used in Russia. A lamella is a flat thin strip with a thickness of 1.2-1.4 mm and a width of 20-150 mm.
3. Using prepregs for amplification (Prepregsystem). A prepreg is a unidirectional canvas or bidirectional fabric pre-impregnated with a binder whose glass transition temperature is lower than the outside air temperature in the factory. Prepregs can be placed on the concrete surface with or without additional binder application. Curing the binder usually requires additional heating.
4. Strengthening the structure by gluing rectangular or round rods made of structural steel into pre-prepared grooves on the surface of the structure (Nearsurfacemounted system).

Rectangular or round rods are formed by pultrusion and are usually transported in bays. In this method, there is no need for such a thorough preparation of the base, as in other cases.
The most common in our country were the 1st and 2nd methods.

METHODOLOGY
Examination and determination of the requirements of normative and technical documentation for composite materials, formation of criteria for evaluating the effectiveness of reinforced concrete structures with composite materials, determination of significance coefficients for criteria for evaluating the effectiveness of reinforced concrete structures with composite materials.

1. The examination was carried out and the necessary and sufficient requirements of normative and technical documentation for composite materials were determined.
2. Criteria for evaluating the effectiveness of reinforced concrete structures with composite materials are formed.
3. The significance coefficients for the criteria for evaluating the effectiveness of reinforced concrete structures with composite materials are determined.
4. 4. A system for evaluating technical solutions for reinforced concrete structures with composite materials is proposed.

RESULTS AND DISCUSSION
Composite materials under tension have a linear relationship between deformations and stresses before failure. The properties of these materials are determined by the number, type, and orientation of the reinforced fibers. The mechanical characteristics of multilayer plastics are determined by testing samples with the appropriate number of layers of fabric (tape) in accordance with GOST 25.601-80.[21] the Mechanical properties of all FAP systems are determined by the results of testing samples of layered material with an estimate of the volume content of fibers, which must be at least 60%.

It should be noted that the dynamic development of the construction materials market at the moment is caused by the appearance of a large number of materials whose adequate selection is a difficult technical task, since it is quite difficult to achieve synchronicity of all the required parameters within a single technical solution. In this regard, it is worth noting that it is advisable to divide all the normalized parameters into significance levels and consider each of them separately for the initial assessment of the effectiveness of the technical decision being made.

For this purpose, it is adequate to test, and systematize and compare the normalized values of GOST and the declared values of the leading Russian manufacturers that occupy the prevailing market share of such technical solutions in the Russian Federation.

Currently, the manufacturers selected for analysis occupy a leading position in the market and are widely used in construction. Their calculation is acceptable boundary indicators and the results of the main characteristics of the proposed products are presented in Table 1. An important aspect of evaluating the effectiveness of a technical solution for strengthening a structure is compliance with manufacturability, namely, in terms of setting the composite material and the surface of the structure or between them.

Table 1 Market analysis of CM manufacturers

Parameter	No. 1 Interaktiva LLC»	№2 CJSC "Prepreg -SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA - holding COMPANY»	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	№9 LLC ZIKA
Coefficient of linear thermal expansion,$°C^{-1}$:									
- longitudinal	$6{,}3·10^{-6}$	$7{,}1·10^{-6}$	$6{,}8·10^{-6}$	$7{,}9·10^{-6}$	$7{,}8·10^{-6}$	$8{,}9·10^{-6}$	$8{,}7·10^{-6}$	$9{,}9·10^{-6}$	$6·10^{-6}$
- cross	$20{,}2·10^{-6}$	$19{,}8·10^{-6}$	$20{,}5·10^{-6}$	$19{,}4·10^{-6}$	$21{,}5·10^{-6}$	$20{,}4·10^{-6}$	$22{,}5·10^{-6}$	$22{,}4·10^{-6}$	$23·10^{-6}$
Coefficient of thermal conductivity W/(m0c)	0,31	0,32	0,33	0,33	0,32	0,32	0,31	0,3	0,3
Elongation, %	0,48	0,85	0,71	0,69	0,58	0,99	1,01	1,03	1,2
Deformity	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Идеально - упругий
Viability	from 80 years	from 80 years	from 80 years	from 80 years	from 80 years	from 80 years	from 80 years	from 80 years	from 80 years
Table 3.1 ending									
Parameter	No. 1 Interaktiva LLC»	CJSC "Prepreg -SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA - holding COMPANY»	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	No. 1 Interaktiva LLC»

Corrosion resistance to aggressive environment	Stainless material	Stainless material	Stainless material	Stainless material	Stainless material	Stainless material	Stainless material	Stainless material	Stainless material
Ecological compatibility	Not toxic	Not toxic	Not toxic	Not toxic	Not toxic	Not toxic	Not toxic	Not toxic	Not toxic
Elastic-plastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic	Perfectly elastic
Width, mm	S512 S612 S812 S1012 S1212 S614 S914 S1214	50 60 80 100 120 60 90 120	M614 M914 M1214	60 90 120	H514	50	50 60 80 100 120 60 90 120	M614 M914 M1214	S512 S612 S812 S1012 S1212 S614 S914 S1214
Thickness, mm	S512 S612 S812 S1012 S1212 S614 S914 S1214	1,2 1,2 1,2 1,2 1,2 1,4 1,4 1,4	M614 M914 M1214	1,4 1,4 1,4	H514	1,4	1,2 1,2 1,2 1,2 1,2 1,4 1,4 1,4	M614 M914 M1214	S512 S612 S812 S1012 S1212 S614 S914

Since such parameters as the coefficient of linear thermal expansion, elongation, deformation, viability, corrosion resistance to aggressive media, environmental friendliness and plasticity in accordance with regulatory documents are close to the normalized ones; and the geometric characteristics of the CM correspond to the requirements set in the technological documentation for manufacturing and correspond to the input control according to GOST 29104.1-91 [14] and GOST 29104.2-91 [11], table 2 is the following (table 2).

Table 2 Market analysis of CM manufacturers

Parameter	No. 1 Interaktiva LLC»	№2CJSC "Prepreg-SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA-holding COMPANY »	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	№№9 LLC ZIKA
Tensile strength σr, MPa	1780	1600	1900	1850	2100	2050	2800	2300	2800
breaking stress σв, σv, MPa	1800	2900	1550	2100	2500	2350	3000	3050	2900
Density g / cm3	1,6	1,5	1,5	1,6	1,58	1,6	1,61	1,64	1,65
The modulus of elasticity, hPa, at least	190	230	165	170	185	250	300	265	300
Glass transition temperature, °C, not less than	37	35	38	37	36	39	40	38	40

The calculation of the efficiency assessment is performed using the formula 1

$$k=\left(\frac{x_{i,j}}{ГОСТ}+\frac{x_{i,j}}{ГОСТ}+\frac{x_{i,j}}{ГОСТ}+\frac{x_{i,j}}{ГОСТ}+\ldots+\frac{x_{n(i,j)}}{ГОСТ}\right)f \quad n=k$$

Where (1)

$x_{i,j}$, $x_{n(i,j)}$ - the declared parameter;
n - number of defined parameters;
GOST-minimum required values;
k - the criterion of effectiveness evaluation. [8]

Table 3 The matrix coefficient calculation

Parameter	No. 1 Interaktiva LLC»	№2CJSC "Prepreg-SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA-holding COMPANY»	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	№№ 9 LLC ZIKA
Direct strength parameters									
Tensile strength σr, MPa	$x_{1:1}$	$x_{2:1}$	$x_{3:1}$	$x_{4:1}$	$x_{5:1}$	$x_{6:1}$	$x_{7:1}$	$x_{8:1}$	$x_{9:1}$
breaking stress σв, σv, MPa	$x_{1:2}$	$x_{2:2}$	$x_{3:2}$	$x_{4:2}$	$x_{5:2}$	$x_{6:2}$	$x_{7:2}$	$x_{8:2}$	$x_{9:2}$
Modulus of elasticity, hPa, not less than	$x_{1:3}$	$x_{2:3}$	$x_{3:3}$	$x_{4:3}$	$x_{5:3}$	$x_{6:3}$	$x_{7:3}$	$x_{8:3}$	$x_{9:3}$
Density g / cm3	$x_{1:4}$	$x_{2:4}$	$x_{3:4}$	$x_{4:4}$	$x_{5:4}$	$x_{6:4}$	$x_{7:4}$	$x_{8:4}$	$x_{9:4}$

Based on the results of calculating (1) the given significance coefficients for the criteria parameters, the following coefficients are set (table 4)

Table 4 The significance coefficient for the critical parameters

Parameter	No. 1 Interaktiva LLC»	№2CJSC "Prepreg-SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA-holding COMPANY»	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	№№9
Direct strength parameters									
Tensile strength σr, MPa	1,1	1,0	1,19	1,16	1,31	1,28	1,75	1,44	1,75
breaking stress σв, MPa	0,62	1,0	0,54	0,72	0,86	0,81	1,03	1,05	1,0
The modulus of elasticity, hPa, at least	0,9	1,09	0,78	0,81	0,88	1,19	1,43	1,26	1,43
Density g / cm3	1,07	1,0	1,0	1,07	1,05	1,07	1,07	1,09	1,1
k	0,92	1,03	0,88	0,94	1,03	1,09	1,32	1,21	1,32

Calculation of the significance coefficient for critical parameters, formula 2:

$$k_x = (k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9)/n$$

Where (2)
k_x - the average measure of the efficiency;
$k_1 - k_9$ - performance evaluation criteria for manufacturers;
n - number of manufacturers.

$$k_x = (k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9)/n = 1{,}08 \text{ [6]}$$

If the value of the performance evaluation criterion is < 1.0, the technical solution with these strength parameters cannot be used.

If the value of the performance evaluation criterion is ≥ 1.0, the technical solution meets the requirements of the regulatory and technical documentation and can be used in the design process. The criterion for the effectiveness of the technical solution depends on the state of the structure, namely the presence of defects in it. To eliminate these defects in different types of floor slabs, different labor costs are required, which directly depend on the labor intensity.

Thus, according to the expert opinion and the test of labor costs for eliminating the defect by various types of composite material by strengthening floor slabs, we summarize the results in table 5.

Table 5 Dependence of labor intensity on the overlap defect

Type of overlap / Type of material	Monolithic	Ribbed	Hollow
Canvases and grids	1,0 / 1,5	0,9	1,0
Laminates	1,0 / 1,5	0,5	1,0

Calculation of efficiency criteria by type of composite material, formula 3; 4:

$$k_{y1} = ((1,0+1,5)/2)+1,1+1,0)/3 = 1,05 \quad (3)$$

$$k_{y2} = ((1,0+1,5)/2)+0,5+1,0)/3 = 0,92, \quad (4)$$

Where

k_{y1} - criteria for the effectiveness of a technical solution made with fabric materials: canvases or grids;

k_{y2} - criteria for the effectiveness of technical solutions made from laminates. [5]

Thus, based on the results of the analysis, we conclude that, for values of the coefficient k_{y1} or k_{y2} < 1.0, the choice of this type of material is not effective, for k_{y1} or k_{y2} ≥ 1.0-it is effective. [4]

Also, an important aspect of evaluating the effectiveness of a technical solution for strengthening a structure is compliance with manufacturability, namely, in terms of setting the composite material and the surface of the structure or between them. According to experts, the most optimal setting and solidification time of the composite material with a construction surface with a security of 90% is 12 hours. Data on manufacturers ' epoxy binders are presented in table 6.

Table 6 The setting time of the composite material and the binder

Parameter	No. 1 Interaktiva LLC»	№2CJSC "Prepreg-SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA-holding COMPANY»	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	№№9 LLC ZIKA
Setting time, h	14	13	15	14	13	11	10	9	9

The efficiency criterion from the setting time is calculated using the formula 5:

$$k = \frac{t_x}{t_n}$$, where (5)

k - The criterion for evaluating the effectiveness;

t_x - optimal setting time;

t_n - stated setting time. [3]

Thus, the obtained values of the efficiency criterion are presented in table 7.

Table 7 Values of criterion of efficiency at the time of setting.

Parameter	No. 1 Interaktiva LLC»	№2CJSC "Prepreg-SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA-holding COMPANY»	№7 LLC "Uralspec - Armatura»	№8 CJSC "PREPREG - MJU»	№№9 LLC ZIKA
the time of setting, h	0,86	0,92	0,8	0,86	0,92	1,09	1,2	1,3	1,3

The average criterion for evaluating efficiency k_Z is calculated using the formula 6:

$$k_Z = (k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9) / n$$

, where (6)

k_Z - average criterion for evaluating performance over time;

$k_1 - k_9$ - performance evaluation criteria for manufacturers;

n - number of manufacturers.

$$k_z = (k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9) / n = 1{,}03$$

According to the results of the study, if k_Z < 1,03 -the criterion for evaluating the effectiveness does not correspond within the acceptable limits;

If k_Z ≥ 1,03– the performance evaluation criterion is within acceptable limits. [2]

Also, when evaluating technical solutions, you cannot ignore such a parameter as the cost of products. Since the construction market is very busy with products from different manufacturers, and the price dynamics is very high, we will present the cost of products in conventional units and reflect this in the table 8.

Table 8 Product prices in conventional units

Parameter	No. 1 Interaktiva LLC»	№2CJSC "Prepreg-SKM»	№3 MBrace	No. 4rosavtodor	NO. 5 NCC LLC»	№ 6 TRIADA-holding COMPANY»	№7 LLC "Ural spec - Armatura»	№8 CJSC "PREPREG - MJU»	№№ 9 LLC ZIKA
Cost of the product c.u.	0,9	1,0	0,8	0,9	1,0	1,1	1,2	1,1	1,2

The average criterion for evaluating efficiency by product cost is calculated using formula 7.

$$k_P = (k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9) / n$$

Where (7)

k_p - average criterion for evaluating performance over time;

$k_1 - k_9$ - performance evaluation criteria for manufacturers;

n - number of manufacturers.

$$k_p = (k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9) / n = 1{,}02$$

According to expert estimates, if k_p < 1,02 – the performance evaluation criterion does not fall within the acceptable limits; if k_p ≥ 1,02 – критерий the evaluation of efficiency is within acceptable limits [1]

Evaluation of the effectiveness of technical solutions can be presented in the form of a criterion function, which is determined by the formula 8:

$$f(k) = \alpha_1 \times k_x + \alpha_2 \times k_y + \alpha_3 \times k_z + \alpha_4 \times k_p,$$

where (8)

$\alpha_1; \alpha_2; \alpha_3; \alpha_4$ - fixed significance coefficients whose numerical values are correspondingly equal 0,25; 0,4; 0,2; 0,15.

The average criterion for evaluating the effectiveness of technical solutions made with flexible composite materials, such as canvases and grids, is determined by the formula 8 [10]and is equal to:

$f(k) =$

0,25×1,08+0,4×1,05+0,92+0,2×1,03+0,15×1,02=1,6

And to evaluate the effectiveness of technical solutions made with rigid composite materials, such as laminates, it is equal to:

$f(k) =$

0,25×1,08+0,4×0,92+0,92+0,2×1,03+0,15×1,02=0,99

Thus, we derive the formula (9) for calculating the effectiveness of technical solutions for reinforcing railway structures with composite materials:

$$f(k_n) = \alpha_1 \times k_{x;n} + \alpha_2 \times k_{y;n} + \alpha_3 \times k_{z;n} + \alpha_4 \times k_{p;n},$$

where (9)

$\alpha_1; \alpha_2; \alpha_3; \alpha_4$ - fixed significance coefficients;

$k_{x;n}; k_{y;n}; k_{z;n}; k_{p;n}$ - criteria for evaluating the effectiveness of calculated parameters by manufacturers. [9]

CONCLUSIONS

For technical solutions made with flexible composite materials such as canvases and meshes:

If $f(k_n)$ < 1,6-the technical solution made with flexible composite materials is not effective, therefore it is necessary to improve the declared characteristics of the NEA or choose another manufacturer;

If $f(k_n)$ ≥ 1,6-the technical solution made with flexible composite materials meets the stated characteristics, is effective and can be applied in practice.

For technical solutions made with rigid composite materials, such as laminates:

If $f(k_n)$ < 0,99 technical solution made with flexible composite materials is not effective, then it is necessary to improve the declared characteristics of the NEA or choose another manufacturer;

If $f(k_n)$ ≥ 0,99 -the technical solution made with flexible composite materials meets the stated characteristics, is effective and can be applied in practice.

Today, leading experts note an increase in the growth rate of the use of composite materials in the reconstruction and strengthening of structures. This method is very promising, has a number of advantages compared to the traditional one, but there are a number of technical difficulties for its mass implementation in practice.

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