Reinforced concrete structures stress-strain state strengthen with composite materials

Valery Telichenko¹, Vladimir Rimshin¹,² and Ekaterina Ketsko²

¹Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia
²Research Institute of Building Physics of the Russian Academy of Architecture and Building Sciences (NIISF RAASN), Moscow, Russia

E-mails: kkuzzina@mail.ru, v.rimshin@niisf.ru

Abstract. In recent years, innovative strengthening of reinforced concrete structures for industrial and civil use by external reinforcement based on carbon fiber has been widely used. However, there are only a few application examples of this amplification technology in the water treatment and sanitation facilities construction and rehabilitation. Based on experimental and practical data, composite amplification systems provide significant results both when working structures in normal conditions, and when they are in aggressive environments. Compared to conventional structural materials, carbon fiber-based composite materials have higher strength, significant fatigue resistance, high elastic modulus, chemical and thermal resistance. This article discusses the calculating method for strengthening reinforced concrete crossbars for coating the construction of an underground purified drinking water reservoir reinforced with composite materials. Based on the calculation methods, the reinforcing feasibility is substantiated. This work was carried out according to the results of a crossbars survey. In order to achieve these goals, a survey was made of the crossbars of the treated drinking water tank, the actual effective loads on the reinforced concrete crossbars were determined, the need to strengthen the examined structures according to the results of calibration calculations was determined, recommendations were developed to strengthen the examined structures of the reservoir construction. A survey of the structures of the structure, as well as an assessment of their technical condition, was carried out taking into account the requirements of current regulatory documents.

1. Introduction

In recent years, innovative strengthening of reinforced concrete structures for industrial and civil use by external reinforcement based on carbon fiber has been widely used. However, there are only a few application examples of this amplification technology in the water treatment and sanitation facilities construction and rehabilitation. Based on experimental and practical data, composite amplification systems provide significant results both when working structures in normal conditions, and when they are in aggressive environments. Compared to conventional structural materials, carbon fiber-based composite materials have higher strength, significant fatigue resistance, high elastic modulus, chemical and thermal resistance. [1-8].

The underground reservoir crossbars survey was carried out, as a result of which the need to strengthen these structures was established. Based on the performed openings, it was found that the
transverse reinforcement pitch of Ø6 mm is 100 mm, however, given the significant loads, reinforced concrete crossbars do not meet the requirements for strength along an inclined section and their strengthening is necessary. Also, during a visual inspection in places, crossbars reinforcement exfoliating corrosion was found (Figure 1).

The verification calculations were performed in order to justify the need for strengthening the underground reservoir reinforced concrete crossbars with carbon fiber. The loads on the tank of purified drinking water reinforced concrete crossbar covering is presented in table 1.

![Figure 1. Reinforcement corrosion.](image)

| Load type               | Standard load, kN / m² | Coefficient | Estimated load, kN / m² | Cargo area, m² | Standard load, kN / m | Estimated load, kN / m |
|-------------------------|------------------------|-------------|-------------------------|----------------|-----------------------|-----------------------|
| Reinforced concrete crossbar | 1,1                      | 4,84        | 5,32                    | 1=2,65 m       |                       |                       |
| Total                    |                         | 4,84        | 5,32                    |                |                       |                       |
| Reinforced concrete slab  | 3                       | 1,1         | 3,3                     | 2,9            | 8,70                  | 9,57                  |
| Reinforced concrete crossbar | 1,1                      | 4,84        | 5,32                    |                |                       |                       |
| Total                    |                         | 13,54       | 14,89                   |                |                       |                       |
| Temporary (table 8.3, normative 20.13330.2011) | 3,05                    | 1,2         | 3,66                    | 3              | 915                   | 10,98                 |
| Total                    |                         | 27,53       | 31,19                   |                |                       |                       |

2. Methods
Concrete class is B35, design characteristics: $R_b=19.5$ MPa, $R_{sm}=R_{b,ser}=260$ MPa, $R_{bt}=1.3$ MPa, $E_b=34520$ MPa, $\gamma_{bi}=0.9$. Working longitudinal bottom reinforcement – 5+7028 A400, $R_c=350$ MPa, $R_{as}=400$ MPa, $E_s=2\times10^5$ MPa. The protective layer is 2.5 cm. Transverse reinforcement – 406 A400, $R_c=350$ MPa, $R_{as}=400$ MPa, $E_s=2\times10^5$ MPa. The pitch is 300 mm.

The crossbar (l=9 m, estimated length 8.6 m) is designed as a beam of T-section with the given dimensions $b \times h = 59 \times 46$ cm, where $b$ is the nominal width and $h$ is the beam height. The beam is articulated. The estimated span is 8.4 m. The calculation was performed using the SCAD Office software package (Arbat).

The crossbar cross-section, the reinforcement layout and the concrete class are adopted on the inspection results of the tank crossbars (Figure 2).
The reliability coefficient for responsibility is $\gamma_n = 1$. The reliability coefficient for responsibility is 1. Figure 3 shows the design solutions and section characteristics of the considered reinforced concrete crossbar.

![Figure 2. Reinforced concrete crossbar cross-section (l=9 m)](image)

**Figure 2.** Reinforced concrete crossbar cross-section (l=9 m)

![Figure 3. Design solution and section characteristics](image)

**Figure 3.** Design solution and section characteristics

Table 2 shows the reinforced concrete crossbar reinforcement characteristics.

| Reinforcement | Class | Working coefficient |
|---------------|-------|---------------------|
| Longitudinal  | A400  | 1                   |
| Transverse    | A300  | 1                   |

Table 3 shows the specified reinforcement.
Table 3. The specified reinforcement

| Length, m | Reinforcement | Section |
|-----------|---------------|---------|
| 8.4       | $S_1 - 40\Omega 28 + 1 \Omega 28$, second row 7 $\Omega 28$ |
|           | Clearance between rows is 2 mm. Transverse reinforcement along the Z axis – 406, the pitch of transverse reinforcement is 300 mm |

The concrete type is heavy. Concrete class is B35. The concrete density is 25 kN / m$^3$. The coefficient of concrete working conditions for accounting long-term loads is adopted $\gamma_{bl} = 0.9$, the resulting coefficient is adopted $\gamma_{b1} = 1$. Environment humidity is 40-75%. Crack opening width is limited. Requirements for the crack opening width are selected from the reinforcement safety condition. The permissible crack opening width with a short opening is 0.4 mm, with a long opening 0.3 mm [9-20].

Table 4 shows the target load values for load 1 (constant). Figure 4 shows the crossbar loading scheme, the calculating results of $M_{\text{max}}$ according to the calculated loads.

Table 4. Values for load 1 - constant

| Load type | Value | Position x | Application load width, s |
|-----------|-------|------------|---------------------------|
|           | 2512 kg/m 0 m 2.65 m | |
|           | 2357 kg/m 2.65 m 5.75 m |

Figure 4. Loading scheme of the crossbar and the calculated results of $M_{\text{max}}$ (kN·m) according to the calculated loads

Load 1 is permanent. The reliability coefficient for the load is 1.1. Table 5 shows the values for load 2 (temporary short-term). Figure 5 shows the crossbar loading scheme, the calculated results of $M_{\text{max}}$ according to the calculated loads.

Table 5. Load 2 - temporary short-term

| Load type | Value | Position x | Application load width, s |
|-----------|-------|------------|---------------------------|
|           | 1098 kg/m 2.65 m 5.75 m | |
Figure 5. The loading scheme of the crossbar and the calculated results of $M_{\text{max}}$ according to the calculated loads.

Load 2 is temporary short-term. The reliability coefficient for the load is 1.2. Table 6 shows the support reactions.

| Table 6. Support reactions |
|-----------------------------|
| Support strength 1 | Support strength 2 |
| $T$ | $T$ |
| by criterion $M_{\text{max}}$ | 10.245 | 9.964 |
| by criterion $M_{\text{min}}$ | 10.245 | 9.964 |
| by criterion $Q_{\text{max}}$ | 12.406 | 9.964 |
| by criterion $Q_{\text{min}}$ | 10.245 | 14.117 |

Table 7 shows the calculated results in reinforced concrete crossbar cross-section to the existing load before reinforcement. Figure 6 shows materials diagram for bending moment.

| Table 7. Calculation results |
|-----------------------------|
| Applying coefficient | Check |
| 0.776 | Strength at ultimate moment in section |
| 0.597 | Deformations in compressed concrete |
| 0.033 | Strain in tensile reinforcement |
| 0.319 | Crack opening width (short term) |
| 0.426 | Crack opening width (long) |
| 0.266 | Strength on a concrete strip between inclined sections |
| 1.135 | Inclined section strength |

Figure 6. Materials diagram for bending moment.
The load-bearing crossbar capacity is provided according to the calculation. The crossbar does not correspond to the transverse forces action along inclined sections due to insufficient transverse reinforcement [21-28]. Thereby the crossbar strengthening is necessary.

3. The crossbar reinforced calculation with a composite material. Results and discussion

The load on the bolt is taken by analogy with table 1.

Design concrete characteristics B35– R_s=19,5 MPa, R_{bn}= R_{b,ser} =260 MPa, R_{bt}=1,3 MPa, E_s=34520 MPa, γ_b1=0,9. Working longitudinal bottom reinforcement – 5+7Ø28 A400, R_s=350 MPa, R_{sn}= 400 MPa, E_s=2x10^5 MPa. The protective concrete layer is 2.5 cm. Transverse reinforcement – 4Ø6 A400, R_s=350 MPa, R_{sn}= 400 MPa, E_s=2x10^5 MPa. The pitch is 300 mm. Equivalent reinforcement for 3 layers of carbon fiber will be equal to:

\[ A_{eq} = \frac{A_{km}}{0.0128 \times 15 \times 3} = 0.576 \text{ cm}^2 \]

where

- \( A_{km} \) – sectional area of the composite material;
- 0.0128 – one canvas thickness (cm);
- 15 – canvas width (cm);
- 3 – number of canvas layers.

\[ A_{eq} = 24465/3568 \times 0.576 = 4.0 \text{ cm}^2 \]

which corresponds to 8 rods Ø8A400, where \( A_{eq} \) – equivalent sectional area of steel reinforcement;

R_{skm} = 2399 MPa – design resistance of the composite material;

R_s = 349.9 MPa – design reinforcement resistance A400.

Equivalent reinforcement from composite clamps corresponds to 8 reinforcement rods Ø8A400, with characteristics – R_s=350 MPa, R_{sn}= 400 MPa, E_s=2x10^5 MPa, the pitch is 200 mm.

The crossbar (l=9 m, estimated length is 8.6 m) is calculated as a beam of T-section with the given dimensions b × h = 59 × 46 cm, where b is the nominal width and h is the height of the beam. The beam is articulated. The estimated span is 8.4 m. The calculation was performed using the SCAD Office software package (Arbat).

The reliability coefficient for responsibility is taken γ_n = 1. Figure 7 shows the design solutions and section characteristics.

Tables 8 and 9 show the reinforcement characteristics of the reinforced concrete crossbar.

**Figure 7.** Design decisions and section characteristics

| Reinforcement | Class | Working coefficient |
|---------------|-------|---------------------|
| Longitudinal  | A400  | 1                   |
| Transverse    | A300  | 1                   |
Table 9. The specified reinforcement

| Length, m | Reinforcement | Cross-section |
|-----------|---------------|---------------|
| 5.4       | $S_t - 4028$, the second row – 4 Ø 28 The distance in the light between the rows – 2 mm. Transverse reinforcement along the Z axis – 8Ø8, the pitch of transverse reinforcement is 200 mm |

The type of concrete is heavy. Concrete class is B35. The concrete density is 25 kN / m$^3$. The concrete working conditions coefficient is accepted $\gamma_{bl} = 0.9$, the resulting coefficient is $\gamma_{bl} = 1$. Air humidity is 40-75%. Crack opening width is limited. Requirements for the width of the crack opening are selected according to the reinforcement safety condition. The permissible crack opening width for short opening is 0.4 mm, for long opening is 0.3 mm [29-33]. Table 10 shows values for load 1 (constant). Figure 8 shows the crossbar loading scheme and the calculating results of $M_{\text{max}}$ according to the calculated loads.

Table 10. Load 1 - constant

| Load type | Value | Position x | Application load width, $s$ |
|-----------|-------|------------|----------------------------|
|           | 16745 kg/m | 0 m | 1 m |

The length is 5.4 m

Figure 8. The loading scheme the calculated results of $M_{\text{max}}$ according to the calculated loads

Table 11 gives values for load 2 (constant). Figure 9 shows the loading scheme the calculated results of $M_{\text{max}}$ according to the calculated loads.

Table 11. Load 2 - constant

| Load type | Value | Position x | Application load width, $s$ |
|-----------|-------|------------|----------------------------|
|           | 2168 kg/m | 1 m | 4.4 m |

The length is 5.4 m
Figure 9. The loading scheme the calculated results of \( M_{\text{max}} \) according to the calculated loads

Load 2 is permanent. The reliability coefficient for the load is 1.1. Table 12 gives the values for load 3 (snow). Figure 10 shows the loading scheme the calculated results of \( M_{\text{max}} \) according to the calculated loads

| Load type | Value | Position | Application load width |
|-----------|-------|----------|------------------------|
|           |       |          |                         |
| Snow      | 540 kg/m | 0 m  | 1 m                    |
| Snow      | 2151 kg/m | 1 m  | 4.4 m                  |
| Snow      | 0.54 kg/m | 1 m  | 4.4 m                  |

Figure 10. The loading scheme the calculated results of \( M_{\text{max}} \) according to the calculated loads

Load 3 is snow. The reliability coefficient for the load is 1.4. Table 13 gives the support reactions.
Table 14 shows the calculation results of the reinforced concrete crossbar after its strengthening with a composite material. Figure 11 shows materials diagram for bending moment.

### Table 13. Support reactions

|                     | Support strength 1 | Support strength 2 |
|--------------------|-------------------|-------------------|
| by criterion $M_{\text{max}}$ | 19.081            | 7.203             |
| by criterion $M_{\text{min}}$ | 19.081            | 7.203             |
| by criterion $Q_{\text{max}}$ | 23.427            | 7.203             |
| by criterion $Q_{\text{min}}$ | 19.081            | 12.862            |

### Table 14. The calculation results

| Applying coefficient | Check                                           |
|----------------------|-------------------------------------------------|
| 0.646                | Strength at ultimate moment in section          |
| 0.464                | Deformations in compressed concrete              |
| 0.03                 | Strain in tensile reinforcement                  |
| 0.289                | Crack opening width (short term)                 |
| 0.385                | Crack opening width (long)                       |
| 0.536                | Strength on a concrete strip between inclined sections |
| 0.73                 | Inclined section strength                        |

**Figure 11.** Materials diagram for bending moment

Based on the calculation, the concrete crossbar strengthening effectiveness is proved to be carbon fiber composite material. The tank crossbar bearing capacity is provided. The crossbar passes to the action of transverse forces along inclined sections during strengthening.

### 4. Conclusions

As a result, a crossbars of the purified drinking water tank cover survey was made with the actual loads determination acting on them, the actual effective loads on the reinforced concrete crossbars were determined, the need to strengthen the examined structures according to the results of verification calculations was determined, recommendations were developed to strengthen the examined reservoir construction structures. In this case, the structures characteristic features were taken into account.

### References

[1] Rimshin V, Aralov R 2019 *Sustainable regeneration of urban areas (using the example of Moscow renovation program)* E3S Web of Conferences, 110, 01011.

[2] Merkulov S, Polyakova N, Rimshin V, Kuzina E, Neverov A 2019 *Construction building systems protection under emergency exposure* E3S Web of Conferences 135, 02014

[3] Kuzina E, Rimshin V 2019 *Experimental and calculated evaluation of carbon fiber reinforcing for increasing concrete columns carrying capacity* E3S Web of Conferences, 97, 04007.

[4] Kuzina E, Rimshin V 2019 *Strengthening of Concrete Beams with the Use of Carbon Fiber* Advances in Intelligent Systems and Computing, 983, pp. 911-919.

[5] Varlamov A, Rimshin V, Tverskoi S 2019 *A method for assessing the stress-strain state of reinforced concrete structures* E3S Web of Conferences, 91, 02046.
[6] Rimshin V, Labudin B, Morozov V, Orlov A, Kazarian A, Kazaryan V 2019 Calculation of Shear Stability of Conjugation of the Main Pillars with the Foundation in Wooden Frame Buildings Advances in Intelligent Systems and Computing, 983, pp. 867-876.

[7] Kuzina E, Rimshin V, Kurbatov V 2018 The Reliability of Building Structures Against Power and Environmental Degradation Effects IOP Conference Series: Materials Science and Engineering, 463 (4), 042009.

[8] Karpenko N I, Eryshev V A, Rimshin V I 2018 The Limiting Values of Moments and Deformations Ratio in Strength Calculations Using Specified Material Diagrams IOP Conference Series: Materials Science and Engineering, 463 (3), 032024.

[9] Varlamov A A, Rimshin V I, Tverskoi S Y 2018 The modulus of elasticity in the theory of degradation IOP Conference Series: Materials Science and Engineering, 463 (2), № 022029.

[10] Krishan A L, Rimshin V I, Astafeva, M A 2018 Deformability of a Volume-Compressed Concrete IOP Conference Series: Materials Science and Engineering, 463 (2), 022063.

[11] Varlamov A A, Rimshin V I, Tverskoi S Y 2018 The General theory of degradation IOP Conference Series: Materials Science and Engineering, 463 (2), 022028.

[12] Rimshin V, Kuzina E 2019 Laboratory Tests Analysis of Reinforced Concrete Structures Strengthened with CRFP IOP Conference Series: Materials Science and Engineering, 661(1)

[13] Kuzina E, Rimshin V, Neverov A 2019 Reserves and exposure assessment of reinforced concrete structures safety while reducing its power resistance E3S Web of Conferences 135, 03010

[14] Kuzina E, Rimshin V, Neverov A 2019 Residual resource of force resistance to Deformation E3S Web of Conferences 135, 01069

[15] Kuzina E, Rimshin V, Neverov A 2019 Residual resource of power resistance during building structures deformation E3S Web of Conferences 135, 03009

[16] Krishan A L, Rimshin V I, Troshkina E A 2018 Strength of Short Concrete Filled Steel Tube columns of Annular Cross Section IOP Conference Series: Materials Science and Engineering, 463 (2), 022062.

[17] Krishan A L, Narkevich M Yu, Sagadatov A I, Rimshin V I 2018 Experimental investigation of selection of warm mode for high-performance self-stressing self-compacting concrete IOP Conference Series: Materials Science and Engineering, 456 (1), 012049.

[18] Telichenko V, Rimshin V, Kuzina E 2018 Methods for calculating the reinforcement of concrete slabs with carbon composite materials based on the finite element model MATEC Web of Conferences, 251, 04061.

[19] Telichenko V, Rimshin V, Eremeev V, Kurbatov V 2018 Mathematical modeling of groundwater pressure distribution in the underground structures by cylindrical form zone (2018) MATEC Web of Conferences, 196, 02025.

[20] Varlamov A A, Rimshin V I, Tverskoi S Y 2018 Planning and management of urban environment using the models of degradation theory (2018) IOP Conference Series: Earth and Environmental Science, 177 (1), 012040.

[21] Rimshin V I, Labudin B V, Melekhov V I, Orlov A, Kurbatov V L 2018 Improvement of strength and stiffness of components of main struts with foundation in wooden frame buildings ARPN Journal of Engineering and Applied Sciences, 13 (11), pp. 3851-3856.

[22] Rimshin V I, Varlamov A A 2018 Three-dimensional model of elastic behavior of the composite Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Tekhnologiya Tekstil'nogo Promyshlennosti, 2018-January (3), pp. 63-68.

[23] Rimshin V I, Pudova A A, Shubin L I 2018 Evaluation of efficiency of use of photovoltaic systems at operation of a residential house Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Tekhnologiya Tekstil'nogo Promyshlennosti, 2018-January (3), pp. 287-293.

[24] Varlamov A A, Rimshin V I, Tverskoi S Y 2018 Security and destruction of technical systems IFAC-PapersOnLine, 51 (30), pp. 808-811.
[25] Cherkas A, Rimshin V 2017 Application of composite reinforcement for modernization of buildings and structures MATEC Web of Conferences, 117, 00027.

[26] Telichenko V I, Rimshin V I, Karelskii A V, Labudin B V. Kurbatov V L 2017 Strengthening technology of timber trusses by patch plates with toothed-plate connectors Journal of Industrial Pollution Control, 33 (1), pp. 1034-1041.

[27] Krishan A L, Rimshin V L, Rakhmanov V A, Troshkina E A, Kurbatov V E 2017 Bearing capacity of short concrete filled steel tube columns of circular cross-section Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti, 370 (4), pp. 220-225.

[28] Krishan A L, Rimshin V I, Telichenko V I, Rakhmanov V A, Narkevich M Yu 2017 Practical implementation of the calculation of the bearing capacity trumpet-concrete column Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti, 2017-January (2), pp. 227-232.

[29] Shubin I L, Zaitsev Y V, Rimshin V I, Kurbatov V L, Sultygova P S 2017 Fracture of high performance materials under multiaxial compression and thermal effect Engineering Solid Mechanics, 5 (2), pp. 139-144.

[30] Kuzina E, Rimshin V 2018 Deformation Monitoring of Road Transport Structures and Facilities Using Engineering and Geodetic Techniques Advances in Intelligent Systems and Computing 692, pp. 410-416.

[31] Krishan A L, Troshkina E A, Rimshin V I, Rahmanov V A, Kurbatov V L 2016 Load-bearing capacity of short concrete-filled steel tube columns of circular cross section Research Journal of Pharmaceutical, Biological and Chemical Sciences 7(3), pp. 2518-2529.

[32] Varlamov A A, Rimshin V I, Tverskoi S Y 2018 Planning and management of urban environment using the models of degradation theory IOP Conference Series: Earth and Environmental Science 177(1), 012040.

[33] Kuzina E, Cherkas A, Rimshin V 2018 Technical aspects of using composite materials for strengthening constructions IOP Conference Series: Materials Science and Engineering 365(3), 032053.