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APPLICATION OF NANOMATERIALS AND NANOTECHNOLOGIES IN CONSTRUCTION

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Experimental studies of reinforced concrete structures in the "HPP supporting piers – powerhouse headwall" system strengthened with prestressed basalt composite reinforcement. Part I

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ABSTRACT
Introduction. With long-term operation of head run-of-river powerhouses of hydroelectric power plants (HPP), technical changes occur that lead to a decrease in operational properties in reinforced concrete structures. To substantiate a new nanotechnology for strengthening long-term operated hydraulic structures based on the use of prestressed reinforcement from nanomaterials (BFRP), a set of experimental studies with elements of computational studies was carried out, taking into account the characteristic features of reinforced concrete structures of HPPs. **Methods and materials.** Experimental studies were carried out on the basis of reinforced concrete models of hydraulic structures "HPP supporting piers – powerhouse headwall" (scale M 1:25), which were manufactured and tested for static impact; after which they were strengthened with external reinforcement made of prestressed BFRP nanomaterial, with rebars installed in two directions: along and across the flow. A 3D finite element model of a run-of-river HPP powerhouse was developed to analyze its stress-strain state (SSS), taking into account seismic actions of more than 8 points (MSK scale) within the framework of the dynamical theory. **Results.** As a result of experimental studies of reinforced concrete models of hydraulic structures "hydroelectric power plant piers – headwall of the HPP powerhouse", the nature of crack formation, the width of crack opening and inter-block construction joints were determined, which were recorded in magnitude higher in non-strengthened reinforced concrete experimental models than in models strengthened with prestressed basalt composite reinforcement. In experimental reinforced concrete models under the acting loads, tensile stresses in the steel reinforcement in the area of the interface of the piers and the headwall were determined, which almost reached the value corresponding to the yield strength. In the article, calculations of the run-of-river HPP powerhouse were performed using the dynamic theory of calculation under the action of seismic loads of more than 8 points (MSK scale). At the same time, deformations of the structure and stresses in its elements in different periods of time (in seconds) were obtained, counting from the beginning of the seismic action. **Discussion.** It was obtained that the new technology of strengthening using reinforcement made of BFRP nanomaterial across and along the river flow leads to a decrease in tensile stresses in steel horizontal reinforcement across the flow in the headwall and in piers by more than 1.5 times with redistribution to basalt composite reinforcement. In case of seismic actions, the operation of the above structures will be more complex and the parameters of this work must be determined by calculations, taking into account all factors that will allow to study and ensure long-term safe operation of HPP structures. To achieve this goal, it is necessary to develop a 3D mathematical model of experimental reinforced concrete structures and verify it using a set of experimental data obtained. Further, the verified mathematical model can be used to calculate the SSS of the HPP powerhouse under the action of a set of loads and influences: static, hydraulic, temperature, seismic. **Conclusion.** On the basis of a set of experimental and computational studies of experimental reinforced concrete models "HPP supporting piers – powerhouse headwall", strengthened with prestressed basalt composite reinforcement, nanotechnology for strengthening reinforced concrete structures of long-term operated hydraulic structures based on the use of prestressed reinforcement from nanomaterials (BFRP) was substantiated, including the load-bearing capacity, displacement, width of opening of inter-block construction joints and cracks, deformations of steel and basalt composite reinforcement depending on the method of strengthening of reinforced concrete structures by external reinforcement.

KEYWORDS: hydraulic structures, HPP supporting piers, HPP powerhouse headwall, inter-block construction joints, nanotechnology of reinforcement, prestress, basalt composite nanomaterial, width of opening of inter-block joints and cracks, displacements

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Экспериментальные исследования железобетонных конструкций системы «бычки ГЭС – напорная стена здания ГЭС», усиленной предварительно напряженной базальтокомпозитной арматурой. Часть I

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АННОТАЦИЯ

Введение. При длительной эксплуатации напорных русловых зданий гидроэлектростанций возникают технические изменения, которые приводят к снижению эксплуатационных свойств в железобетонных конструкциях. Для обоснования новой технологии (нанотехнологии) усиления длительно эксплуатируемых гидротехнических сооружений на основе применения предварительно напряженной арматуры из наноматериалов (базальтокомпозитной арматуры) проведен комплекс экспериментальных исследований с элементами расчетных исследований, учитывающий характерные особенности железобетонных конструкций ГТС. **Методы и материалы.** Экспериментальные исследования проводились на основе железобетонных моделей гидротехнических сооружений «бычки ГЭС – напорная стена здания ГЭС» (масштаб М 1:25), которые были изготовлены и испытаны на статическое воздействие; после чего они были усилены внешним армированием из наноматериала – предварительно напряженной базальтокомпозитной арматуры, установленной в двух направлениях: вдоль и поперек потока. Была разработана пространственная конечно-элементная модель руслового здания ГЭС для расчетных исследований НДС с учетом сейсмических воздействий более 8 баллов в рамках динамической теории. **Результаты.** В результате экспериментальных исследований опытных железобетонных моделей гидротехнических сооружений «бычки ГЭС – напорная стена здания ГЭС» определен характер трещинообразования, ширина раскрытия трещин и межблочных строительных швов, зафиксированных по величине выше в неусиленных железобетонных опытных моделях, чем в усиленных предварительно напряженной базальтокомпозитной арматурой моделях. В опытных железобетонных моделях при действующих нагрузках определены растягивающие напряжения в стальной арматуре в зоне сопряжения бычков и напорной стены, которые практически достигли величины, соответствующей пределу текучести. В настоящей работе были выполнены расчеты руслового здания ГЭС с применением динамической теории расчета при действии сейсмических нагрузок более 8 баллов. При этом были получены деформации сооружения и напряжения в его элементах в различные периоды времени (в секундах), отсчитывая от начала сейсмического воздействия. **Обсуждение.** Было получено, что новая технология (нанотехнология) усиления с применением наноматериала, предварительно напряженная базальтокомпозитной арматуры – поперек и вдоль потока, – приводит к снижению растягивающих напряжений в стальной горизонтальной арматуре поперек потока в напорной стене и в бычках более чем в 1,5 раза с перераспределением на базальтокомпозитную арматуру. При сейсмических воздействиях работа вышеуказанных конструкций будет более сложной и параметры этой работы необходимо определять расчетами с учетом всех факторов, которые позволят изучить и обеспечить длительную безопасную эксплуатацию гидротехнических сооружений ГЭС. Для достижения этой цели необходимо разработать трехмерную математическую модель железобетонных экспериментальных конструкций и провести её верификацию с использованием комплекса полученных экспериментальных данных. Далее верифицированную расчетную математическую модель возможно применить для расчетов НДС здания ГЭС при действии комплекса нагрузок и воздействий: статических, гидравлических, температурных, сейсмических. **Заключение (выводы).** На основе проведенного комплекса экспериментальных и расчетных исследований опытных железобетонных моделей «бычки ГЭС – напорная стена здания ГЭС», усиленных предварительно напряженной базальтокомпозитной арматурой, была обоснована нанотехнология усиления железобетонных конструкций длительно эксплуатируемых гидротехнических сооружений на основе применения предварительно напряженной арматуры из наноматериалов (базальтокомпозитной

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арматуры), в том числе определялись несущая способность, перемещения, ширина раскрытия межблочных строительных швов и трещин, деформации стальной и базальтокомпозитной арматуры в зависимости от способа усиления железобетонных конструкций внешним армированием.

КЛЮЧЕВЫЕ СЛОВА: гидротехнические сооружения, бычки ГЭС, напорная стена здания ГЭС, межблочные строительные швы, нанотехнология усиления, предварительное напряжение, наноматериал - базальтокомпозитная арматура, ширина раскрытия межблочных швов и трещин, перемещения

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ НАУЧНОЙ РАБОТЫ, РЕЗУЛЬТАТОМ КОТОРОЙ СТАЛА ПУБЛИКАЦИЯ: Работа выполнена инициативно из личных средств авторов при научно-технической поддержке филиала АО «Институт Гидропроект»–«НИИЭС».

ДЛЯ ЦИТИРОВАНИЯ:
Рубин О.Д., Антонов А.С., Алмасри А. Экспериментальные исследования железобетонных конструкций системы «бычки ГЭС – напорная стена здания ГЭС», усиленной предварительно напряженной базальтокомпозитной арматурой. Часть I. *Нанотехнологии в строительстве.* 2026; 18(4):483–494. https://doi.org/10.15828/2075-8545-2026-18-4-483-494. – EDN: PRJLOE.

INTRODUCTION

Run-of-river hydroelectric power plants represent a significant part of the operated HPPs [1-5]; being in river beds, they are part of the structures of the pressure front.

Figure 1 shows a vertical section along the flow through the powerhouse of a hydroelectric station, depicting the main load-bearing hydraulic structures: piers, the upstream wall of the powerhouse, and others. These structures are designed to withstand loads from the headwater and transfer them to other supporting elements.

In the course of long-term operation of head run-of-river powerhouses of HPPs, deviations from the design prerequisites arise, which are caused by non-design displacements and settlements, opening of inter-block construction joints and cracks, changes in the condition of concrete and reinforced concrete structures and their foundations, changes in the nature and magnitude of the acting loads, etc., which leads to a decrease in the parameters of safe operation.

During the design period of most of the hydroelectric facilities [6], seismic calculations were carried out on the basis of the linear-spectral theory in accordance with SNiP II-A.12-62 [7] and SNiP II-7-81* [8] using the OSR-97 maps used at that time. Currently, updated standard SP 14.13330.2018 [9] is in force, providing for an increase in seismicity by 1–2 points (MSK scale) in accordance with the OSR-2015 maps, as well as a dynamic theory of calculations of hydraulic structures of the I and II classes based on accelerograms.

The calculations carried out to substantiate the strength and stability of the design solutions of the run-of-river HPP powerhouses met the requirements of regulatory documents.

However, in the course of long-term operation of HPPs, the main load-bearing reinforced concrete structures undergo deviations from the design prerequisites,

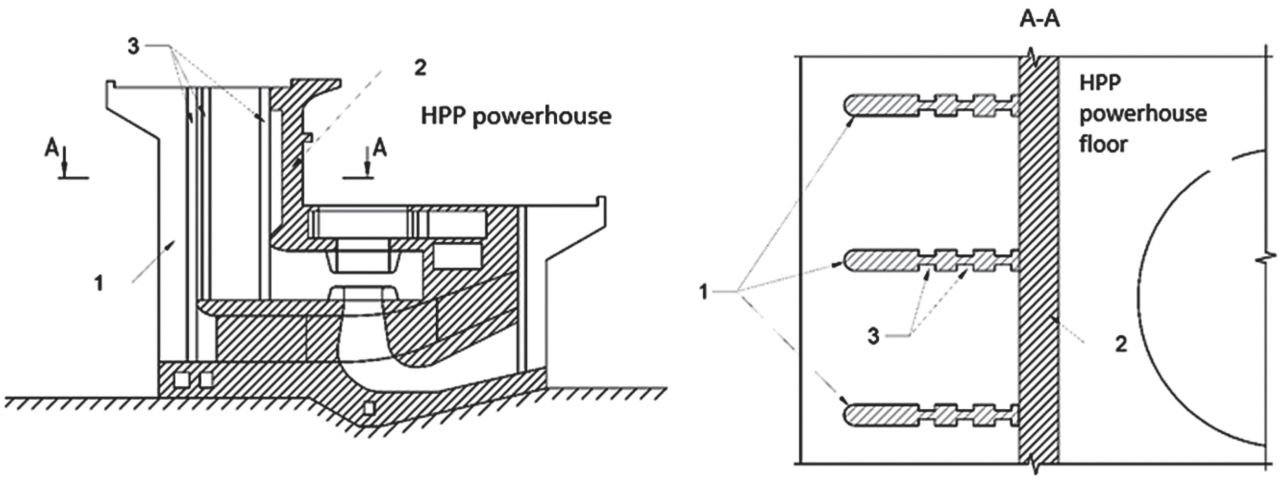

Fig. 1. Vertical section along the flow of the head run-of-river powerhouse of the HPP: 1 – piers; 2 – upstream wall of the powerhouse. Section A-A shows: 1 – piers; 2 – upstream wall of the powerhouse; 3 – gate slots

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including changes in strength and deformation characteristics, the nature of loads, etc.

In this regard, research and engineering personnel must solve the problems of ensuring safety during the operation of HPPs in conditions of reduced safety margins, changes in the nature of existing loads, including seismicity of higher intensity.

The problem of substantiating nanotechnology for strengthening reinforced concrete structures is widely studied by various scientists, while nanomaterials (composite materials) have become widespread, allowing to provide the necessary reserves of bearing capacity practically without changing their mass and size dimensions.

Studies [10] have evaluated the characteristics of nanomaterial – basalt composite (BFRP) reinforcement in contrast to carbon FRP (CFRP) and steel reinforcement. Bendable and compressed models are considered. At the same time, other characteristics (such as mechanical, thermal, chemical) of the BFRP, CFRP samples and steel reinforcement were determined. An increase in ultimate stresses in composite rebar was recorded in comparison with steel rebar with a simultaneous decrease in ductility. Composite rebars made of BFRP and CRFP were noted for their increased resistance to aggressive environmental influences.

Studies [11] consider BFRP reinforcement based on basalt, epoxy and polyester resin fibers. BFRP reinforcement with continuous spiral finning, which is formed by basalt fiber to improve adhesion to concrete. The advantages of BFRP reinforcement in comparison with steel reinforcement are revealed:

- the tensile strength is twice that of steel reinforcement;
- unlike steel reinforcement, it is not subject to corrosion;
- weight is 89% less than steel reinforcement;
- the coefficient of thermal expansion is close to concrete;
- basalt fibers are not conductors of moisture;
- it is a dielectric;
- is not a conductor of magnetic fields;
- it operates in the range from –70 °C to +100 °C, including in fire-resistant rooms.

So, the service life of reinforced concrete structures including hydroelectric power plants can be increased by using reinforcement made of BFRP nanomaterial.

The article [12] discusses the characteristics of concrete structures reinforced with a basalt composite reinforcement, after exposure to freeze-thaw cycles. As a result of pull-out tests after 100 and 200 freeze-thaw cycles (at a freezing point of –20 °C), almost the same strength of adhesion of the BFRP reinforcement to the structure was recorded, which is important for hydraulic structures located in different climatic zones.

In the course of testing structures with basalt composite reinforcement during bending [13], the effectiveness of using BFRP in strengthening and repairing long-term using structures was achieved, in contrast to traditional methods of strengthening. At the same time, it was noted that BFRP reinforcement had greater strength and a lower modulus of elasticity (compared to steel reinforcement), which was consistent with [10].

The article [14] is devoted to the study of bending concrete elements with BFRP reinforcement. In total, eight concrete structures with a length of 3100 mm and a cross-section of 200×300 mm were manufactured and tested to failure. Six structures were reinforced with BFRP reinforcement with a diameter of 8, 12 and 16 mm with a ribbed surface, and two control reinforced concrete structures were reinforced with steel reinforcement of 10M and 15M. It is noted that all structures failed by concrete crushing in the compression zone of concrete with high deformability.

The article notes that the behavior of structures made of BFRP nanomaterial is significantly influenced by the axial stiffness of the bending basalt composite reinforcement (E_fA_f). It should be noted that the experiments performed confirm the effectiveness of using BFRP prestressed rebars, which makes it possible to realize the high strength and deformability of nanomaterials.

To study the bearing capacity of concrete structures reinforced with basalt composite reinforcement [15], 8 models with BFRP reinforcement with a diameter of 10, 13, 16 and 25 mm, having low, average and high reinforcement ratios were tested. All specimens failed by crushing of the concrete in the compression zone, while the high reinforcement ratio reduces the deflection of the structures to some extent. The authors note that the maximum loads perceived by structures directly depend on the reinforcement ratio. The article also presents a comparison of the forecasting model with experimental models, which confirmed the reliability of the study.

The article [16] presents the results of experiments in the bending of prestressed structures reinforced with BFRP nanomaterial, including the assessment of prestress losses. 5 structures were manufactured, of which three are reinforced with BFRP rebars with a diameter of 6 mm, prestressed to 20%, 30% and 40% of the prestressed limit level. The prestress losses were monitored using strain gauges on the rebars. In addition, the two inspection structures were reinforced with stressed BFRP and steel bars of the same cross-sectional area, respectively. The dimensions of all samples were 125×200×1900 mm.

Based on the results of experiments on structures (reinforced with nanomaterial) tested under bending to failure, the following conclusions are presented:

- prestressing of BFRP reinforced samples with over 30% of the ultimate tensile capacity of the bars improved the serviceability performance of the beams to a level higher than that of the steel reinforced sample;

- limit deflections of prestressed structures are lower compared to non-stressed structures with BFRP;
- the formation of cracks on the surface of the structures was measured for prestressed structures according to the level of prestress.

It should be noted that the studies carried out do not contain data on the strengthening of the above structures by the external reinforcement system.

The aim of the research [17] was to study the bending of structures strengthened using the rebar near surface mounted technology (NSM) with a BFRP nanomaterial to assess the effectiveness of reinforced concrete structures strengthening. In addition, nanotechnology for prestressing near the surface of structures (PNSM) was considered, which to a certain extent combines two well-known technologies of "external prestress" and "NSM".

This study examined:

- non-reinforced and reinforced samples;
- BFRP and GFRP reinforcement;
- NSM and PNSM strengthening method;
- 30% and 50% prestressing levels (from the ultimate extensibility of BFRP);
- placement of composite reinforcement from below or from the side using the NSM method.

In the course of the research, an advantage was revealed when using the BFRP nanomaterial to strengthen concrete elements using the NSM and PNSM methods, as well as reinforcement from the BFRP nanomaterial.

The article [18] presents the results of comparison basalt composite reinforcement (BFRP) and the steel reinforcement in terms of the main characteristics.

Shear failure of concrete elements reinforced with prestressed BFRP in the absence of stirrups reinforcement in them was investigated. The article presents the results of numerical studies within the framework of the ANSYS software, which were in good agreement with experimental data. The advantage of nanotechnology for strengthening reinforced concrete structures in long-term operation is confirmed.

The paper [19] presents the results of experimental studies of concrete structures with prestressed reinforcement.

The results of the experiments were analyzed, computational nonlinear models were created in the ANSYS software, and a fairly good coincidence of experiments and calculations in terms of the nature of the fracture and numerical values of the destructive load, as well as the distribution of stresses, was obtained.

The article [20] analyzes the test results of concrete structures with prestressed reinforcement made of basalt composite nanomaterial, including those with and without external stirrups. It is noted that the use of concrete structures with steel reinforcement under the influence of water and salt environments, as well as chemicals due to intense corrosion, is problematic, and therefore the use of nanomaterial BFRP reinforcement is necessary. To prevent intense cracking in structures, BFRP reinforcement must be prestressed. Two non-strengthened models under shear action were investigated. Two models, strengthened with external steel stirrups, failed due to bending when the reinforcement reached its yield point. Thus, to ensure strength, it is necessary to take into account the combined effect of bending moment and shear in the span of the structure.

The findings published in references [10–20] confirm that the content of this article is undoubtedly relevant and necessary for the implementation of nanotechnological strengthening of reinforced concrete structures of HPPs in conditions of long-term operation, including high seismic activity.

Nanomaterial composite rebar has the following advantages over steel rebar:

- tensile strength is 2.5–3.0 times higher;
- weight more than 4 times lower;
- high resistance to the alkaline environment of concrete and other aggressive environments;
- dielectric.

The expediency of using basalt composite reinforcement is justified by the optimal ratio of strength characteristics and cost.

The authors of this article have carried out a set of experimental and computational studies to substantiate the nanotechnology of reinforcement in order to increase the bearing capacity of reinforced concrete structures of HPPs.

METHODS AND MATERIALS

The authors of the article carried out experimental studies of reinforced concrete models "hydroelectric power plant piers – headwall of the HPP powerhouse", strengthened with prestressed basalt composite reinforcement, including determining the bearing capacity, displacements, opening of inter-block construction joints and cracks width, deformations of steel and basalt composite reinforcement depending on the method of reinforced concrete structures strengthening with external reinforcement.

Calculations of SSS on the action of static loads and seismic forces exceeding 8 points (MSK scale) were also carried out in order to determine the need to strengthen the HPP powerhouse structures by the methods presented in the experimental part of the study.

The stages of work were as follows:

- Development of a mathematical model of a run-of-river HPP powerhouse and computational studies of SSS using the ANSYS software under the action of static loads (weight of structures and equipment, hydraulic load from the headwater, vertical water pressure on the base of the structure, etc.), temperature and seismic effects.

– Laboratory tests of prototypes of hydraulic structures (piers and headwall of the powerhouse) with inter-block construction joints, with reinforcement with steel rebars and external prestressed basalt composite rebars.

For the experimental models "hydroelectric power plant piers – headwall of the HPP powerhouse", B30 class concrete, steel (reinforcement ratio $\mu < 0.005$) and basalt composite reinforcement were used (Table 1).

Experimental studies on physical reinforced concrete models were carried out in the laboratory of the branch NIIES of Institute Hydroproject, JSC using a specialized metal 100-ton stand and hydraulic equipment:

1. Hydraulic jack (static loading) DG-50:
   - created force – 50 tons;
   - piston stroke length – 60 mm;
   - working pressure – 45.5 MPa.
2. Hydraulic pumping station MP700 ENERPAC:
   - rated pressure – 70.0 MPa;
   - piston stroke length – 26.5 mm.
3. Hydraulic jack "CONER" (tensioning of reinforcing bars, Fig. 2)
   - The maximum tension pressure is 400 atm.

Measuring equipment:

1. TML FLA-10-11 strain gauges with a 10 mm base (for reinforcement) with a resistance of 120 Ohm. Num-

Table 1. Characteristics of the materials used to make the models

No.	Characteristics	Concrete of class B30, MPa	Reinforcement, MPa	
			Steel	Basalt Composite
1	Compressive Strength	$R_{bn} = 22.0$	–	–
2	Tensile strength	$R_{bt} = 1.80$	$R_{sn} = 390$	$R_{fn} = 1000$
3	Modulus of deformation	$E_b = 32\,500$ (compression)	$E_s = 200\,000$ (tension)	$E_{fn} = 50\,000$ (tension)

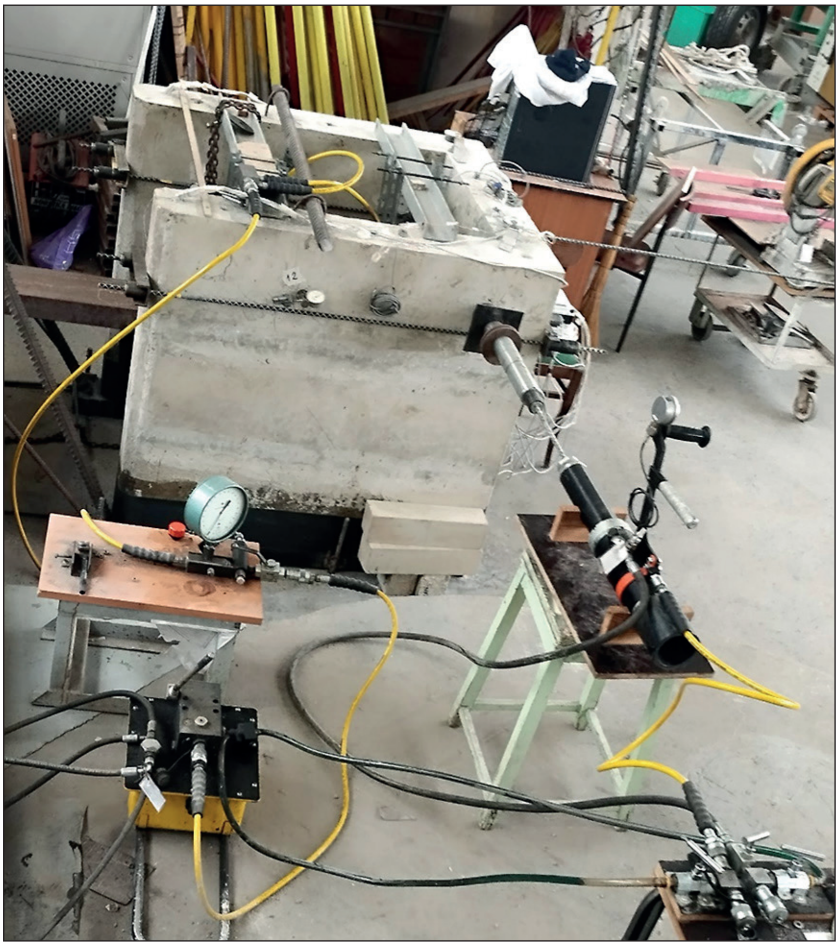

Fig. 2. Testing of an experimental reinforced concrete model (the process of tensioning basalt composite reinforcement is shown):
– hydraulic pumping station "ENERPAC";
– hydraulic jack "CONER";
– oil distributors

ber in the Russian State Register of Measuring Instruments – 79148-20.

2. Strain gauge station "NTP Horizont". Number in the Russian State Register of Measuring Instruments – 79484-20 (Table 2).

3. Dial gauges ZICHT. Number in the State Register of Measuring Instruments – 76658-19 (measurement of the opening width of inter-block construction joints and cracks; measurement of deflections). The scale division is 0.005 mm. The largest difference in the errors of the direct course of the indicator: within the working section of the scale – 0.005 mm and within the normalized section of the scale – 0.003 mm.

Initially, the data of earlier laboratory studies were analyzed to determine the prestress losses in the basalt composite reinforcement installed in the concrete element, as well as to determine the strength of the concrete structure reinforced with the prestressed basalt composite reinforcement [16, 21, 22].

Analysis of the data of the previously performed laboratory studies showed that the pretension losses of the steel reinforcement after 90 hours amounted to 2.9–4.0%, while the losses of the prestress of the basalt composite reinforcement amounted to 3.4% and remained further at the same level.

To solve the above problem of substantiating the nanotechnology of strengthening of reinforced concrete structures of the system "hydroelectric power plant piers – headwall of the HPP powerhouse", using prestressed basalt composite reinforcement, the authors conducted laboratory tests of experimental models that take into account the characteristic features of hydraulic reinforced concrete.

The presented work was carried out in continuation and development of previous studies [23].

For experimental studies, experimental reinforced concrete models "hydroelectric power plant piers – headwall of the HPP powerhouse" were developed at a scale of M 1:25 (Fig. 3), which have inter-block construction joints (concreting of the models was carried out in three blocks in order to create inter-block joints), reinforcement with ⌀12A400 steel reinforcement.

The experimental reinforced concrete models were reinforced in two directions with a nanomaterial – prestressed basalt composite reinforcement (Fig. 4) after the cracks were formed. The stages of reinforcement and testing of the experimental models are shown in Fig. 5.

In this work, calculations of the run-of-river HPP powerhouse were performed using the dynamic theory of calculation under the action of seismic loads of more than 8 points (MSK scale).

At the same time, deformations of the structure and stresses in its elements in different periods of time (in seconds) were obtained, measured from the onset of seismic loading.

Figure 6a shows the stress state in the structures of the HPP powerhouse under the action of static loads and seismic actions based on the dynamic theory of calculation in the time periods of 2.62 sec and 4.94 sec from the beginning of the seismic action.

During the process of seismic action, there is a redistribution of the acting forces and, accordingly, the stress state.

The maximum tensile stresses reaching 4.7 MPa act in the headwall of the HPP powerhouse (Fig. 6a) in 2.62 seconds after the beginning of the seismic action, and in 4.94 seconds in the piers of the HPP powerhouse (Fig. 6b) the maximum tensile stresses (up to 3.5 MPa) occur.

Under the influence of tensile stresses that exceed the tensile strength of concrete, inter-block construction joints are opened and cracks are formed and opened, including a violation of the contact between the bottom of the HPP powerhouse and the foundation (Fig. 5), which negatively affects the stability and strength of the HPP powerhouse.

Based on the presented results of the calculations of the HPP powerhouse under the seismic action with an intensity of more than 8 points (MSK scale) within the framework of the dynamic theory, there is a need to take measures to strengthen and increase the seismic resistance of the reinforced concrete structures of the HPP powerhouse. At the same time, the use of nanotechnology of strengthening seems to be the most effective.

The experimental models included reinforcing cages made of ⌀12 A400 steel reinforcement (Fig. 7) equipped with strain gauges with a 10 mm base. During the experimental studies, the following characteristics were recorded:

a) the nature of crack formation (including their length and width of opening);

Table 2. Strain gauge station "NTP Horizont" features

1	Number of measuring channels	32
2	Supported bridge circuits	full-bridge, half-bridge, quarter-bridge
3	Nominal resistance of strain gauge transducers	50–1000 ohms
4	Conversion Ratio Measurement Ranges	±5; ±10 mV/V
5	Limits of permissible relative error of oscillation frequency measurements	±5×
6	External interfaces	RS – 485, USB; Bluetooth

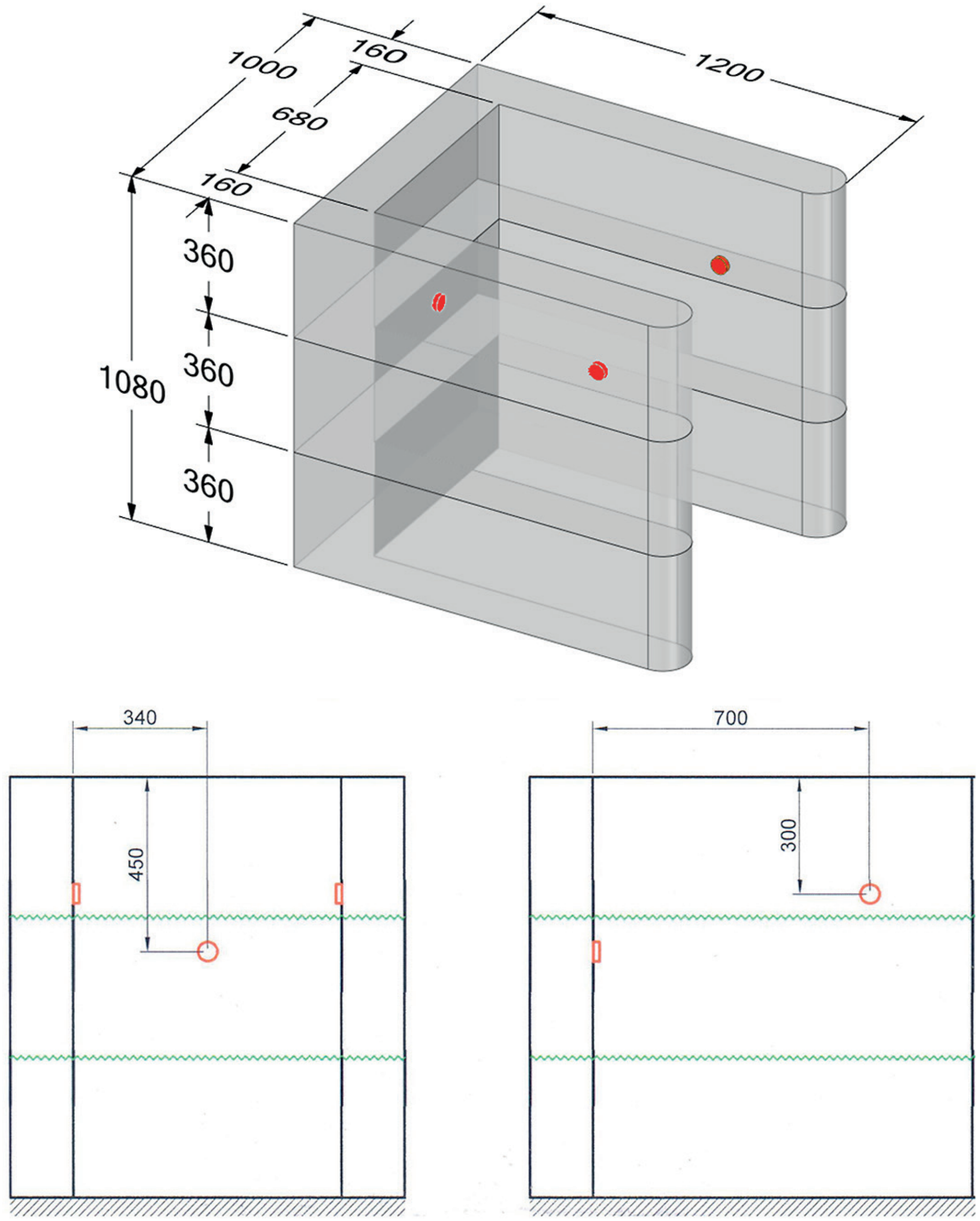

Fig. 3. Experimental reinforced concrete model "hydroelectric power plant piers – headwall of the HPP powerhouse" in scale M 1:25 with the location of the places of action of experimental loads (dimensions are given in mm)

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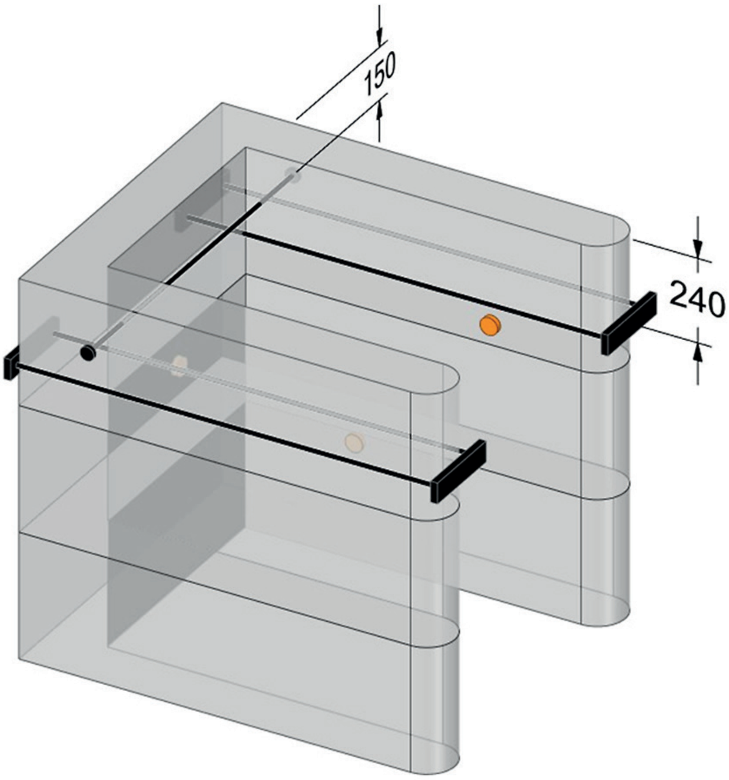

Fig. 4. Schemes of placement (along and across the flow) of prestressed basalt composite reinforcement for strengthening the experimental models

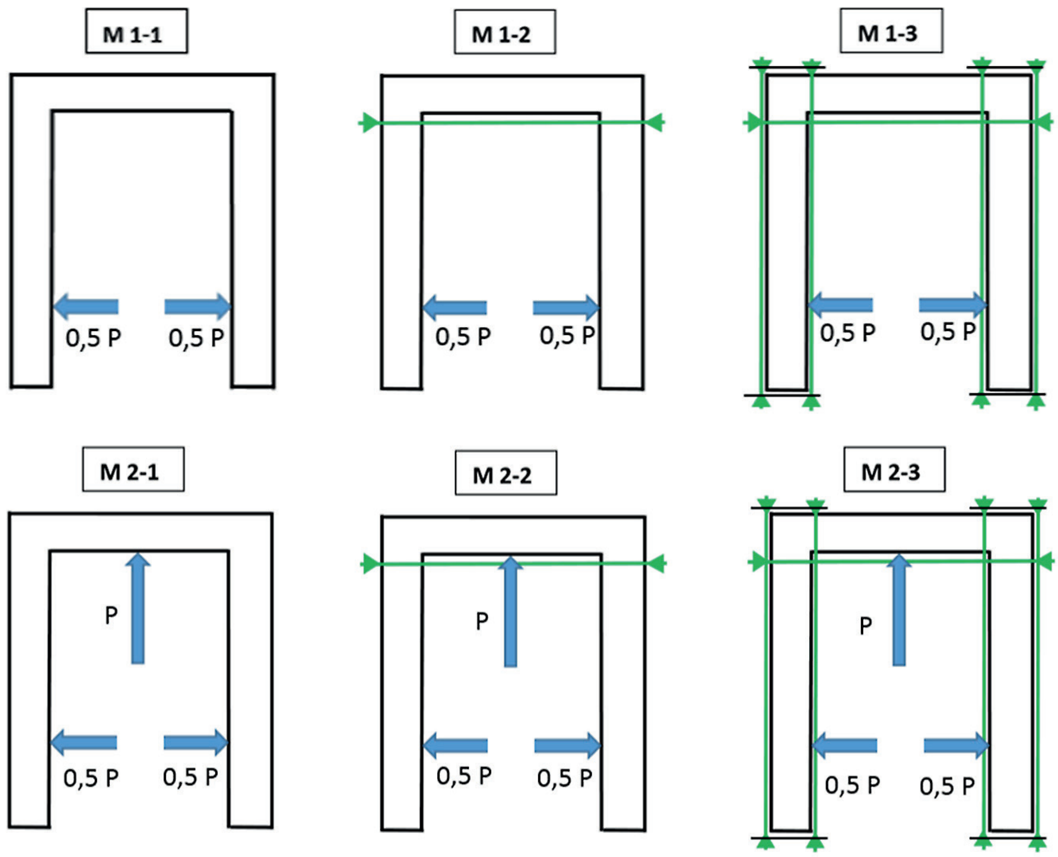

Fig. 5. Stages of reinforcement and testing of experimental reinforced concrete models

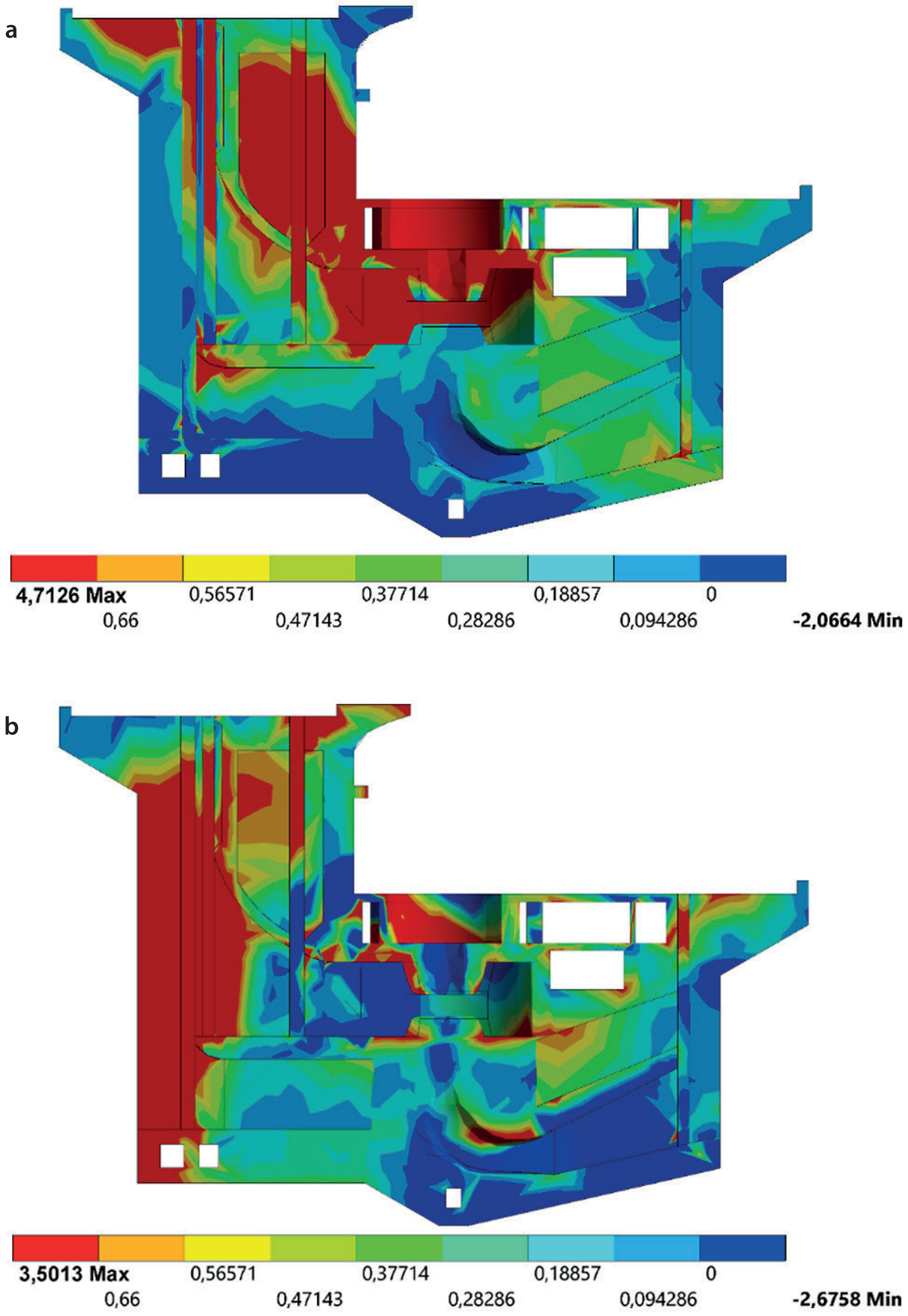

Fig. 6. Main stress distribution pattern, MPa: a – in the headwall of the powerhouse (2.62 seconds after the start of the seismic action); b – in piers (4.94 seconds after the start of the seismic action)

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Fig. 7. Spatial reinforcement cage of reinforced concrete models with installed formwork of the 1st tier of concreting

b) the relative displacement between piers;

c) stresses in steel reinforcement;

d) stress increments in prestressed basalt composite reinforcement;

e) the strength of the experimental models "hydroelectric power plant piers – the headwall of the HPP powerhouse".

The prestress of basalt composite reinforcement in the experimental models M1-2, M1-3, M2-2 and M2-3 was 300 MPa, determined as $0.30 \cdot R_{f,n} = 0.30 \cdot 1000 = 300$ MPa (ratio 0.30 does not exceed 0.45 in accordance with clause 7.1.1. of SP 295.1325800.2017 [24]).

To be continued

REFERENCES

1. Arshenevsky N.N., Gubin M.F., Mityurev E.L., Mikhailov I.E., Orlov V.A., Popov A.I. *Hydroelectric Power Plants.* M.: Energoatomizdat; 1987. – EDN: SNSPBJ (in Russian).
2. Raja A.K., Srivastava A.P., Dwivedi M. Power Plant Engineering. New Delhi: New Age International. 2006;354. ISBN 81-224-1831-7. Available from: https://www.academia.edu/attachments/63581667/download_file (access date 05.04.2026)
3. Lenkov A.Yu., Fisenko V.F. Experience gained from operation of the hydraulic structures of the Votkinsk hydroelectric power plant. *Power Technology and Engineering*. 2017;51(1):33-39. https://doi.org/10.1007/s10749-017-0779-y – EDN: XNDQPU.
4. Vasilevskaya L. S., Anufrenkova, P. S., Gracheva D. A. Evaluation of Concrete Structure Condition of the Volzhskaya Hydroelectric Power Plant. *Power Technology and Engineering.* 2018;52(2):181-184. https://doi.org/10.1007/s10749-018-0929-x – EDN: YBPZOH.
5. Rodrigues R. V. Structural Design of a Surface Hydropower Plant. *Technical University of Lisbon*. 2014;1-9. Available from: https://fenix.tecnico.ulisboa.pt/downloadFile/563345090413168/resumo.pdf (access date 05.04.2026)
6. Rubin O.D., Lisichkin, S.E., Baklykov I.V., Almasri A. Objectives of the Computational Studies of the Long-term Operational Run-of-River Buildings of Tishrin and Baath HPPs Located in Seismic Areas of Syria. *VI International Scientific Conference Construction Mechanics, Hydraulics & Water Resources Engineering (CONMECHYDRO 2024)*. Karshi; Uzbekistan. https://doi.org/10.1063/5.0279432
7. SNiP A-II. 12-62 *Construction in seismic areas. Design norms*. Moscow. 1963; 54 (in Russian).
8. SNiP 11-7-81* *Construction in seismic areas. Design norms*. Moscow. 2006; 44 (in Russian).
9. SP 14.13330.2018 *Construction in seismic areas. Updated edition of SNiP 11-7-81**. Moscow. 2018; 115 (in Russian).
10. Zaki M., Tobaa A., Shehata A. Potential advantages of basalt FRP bars compared to carbon FRP bars & conventional steel. *Australian Journal of Civil Engineering*. 2020;19(1):1-16. https://doi.org/10.1080/14488353.2020.1816638 – EDN: NENRWF.
11. Subramanian N. Sustainability of RCC Structures using Basalt Composite Rebars. *The Master builder*. 2010;(9):156-164. Sustainability of RCC using Basalt composite Rebars Master Builder Sept2010
12. Mohamed-Akram Khanfour, Ahmed El Refai. Effect of freeze-thaw cycles on concrete reinforced with basalt fiber-reinforced polymers (BFRP) bars. *Construction and Building Materials*. 2017;145:135-146. https://doi.org/10.1016/j.conbuildmat.2017.03.237

ISSN 2075-8545 (online)

Nanotechnologies in construction | 2026; 18 (4):
Нанотехнологии в строительстве | 483–494

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13. Elamathi E., Priyanka R., Sangeetha V. Flexural Study on Basalt Rebar Reinforced Concrete Beams. *Journal of Engineering*. 2018; 8(1):01-05. 1, 01-05.pdf

14. Fareed Elgabbas; Ehab A. Ahmed, M.ASCE; Brahim Benmokrane. Flexural Behavior of Concrete Beams Reinforced with Ribbed Basalt-FRP Bars under Static Loads. *Journal of Composites for Construction*. 2016;21(3). https://doi.org/10.1061/(ASCE)CC.1943-5614.0000752

15. Thilan Ovitigala, Mustapha A. Ibrahim, Mohsen A. Issa. Serviceability and Ultimate Load Behavior of Concrete Beams Reinforced with Basalt Fiber-Reinforced Polymer Bars. *ACI Structural Journal*. 2016;113(4):757-768. https://doi.org/10.14359/51688752

16. Pavlovic A., Donchev T. Pretensioned BFRP reinforced concrete beams: Flexural behaviour and estimation of initial prestress losses. *MATEC Web of Conferences*. 2019;289. https://doi.org/10.1051/matecconf/201928909001

17. Sokairge H., Elgabbas F., Elshafie H. Structural behavior of RC beams strengthened with prestressed near surface mounted technique using basalt FRP bars. *Engineering Structures*. 2022;250(9):113489. https://doi.org/10.1016/j.engstruct.2021.113489 – EDN: VQHDNK

18. Thorhallsson E., Zhelyazov T., Gunnarsson A., Snaebjornsson J.T. Concrete beams reinforced with prestressed basalt bars. *Concrete – Innovation and Design, fib Symposium*. Copenhagen; 2015. (PDF) CONCRETE BEAMS REINFORCED WITH PRESTRESSED BASALT BARS

19. A. Gunnarsson, E. R. Thorhallson, J. Th. Snaebjornsson. Simulation of Experimental Research of Concrete Beams Prestressed with BFRP Tendons. *Nordic Concrete Research Symposium. Reykjavik, Iceland*. 2014. (PDF) SIMULATION OF EXPERIMENTAL RESEARCH OF CONCRETE BEAMS PRESTRESSED WITH BFRP TENDONS

20. E.Thorhallsson, S. H. Gudmundsson. Test of prestressed basalt FRP concrete beams with and without external stirrups. *Proceedings of Fib symposium Engineering a Concrete future: Technology, modelling & Construction. At: Tel Aviv*. Israel; 2013. (PDF) Test of prestressed basalt FRP concrete beams with and without external stirrups

21. Bellendir E.N., Rubin O.D., Lisichkin, S.E., Zyuzina, O.V. Experimental Study into Prestress Losses of Basalt Composite Reinforcement Used in the Composition of Concrete Elements. *Power Technology and Engineering*. 2021;54(5):605–608. https://doi.org/10.1007/s10749-020-01259-y – EDN: VLSBAJ.

22. Pearson M., Donchev T., Salazar J. Long-Term Behaviour of Prestressed Basalt Fibre Reinforced Polymer Bars. *The 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering. Procedia Engineering*. 2013;54:261–269. https://doi.org/10.1016/j.proeng.2013.03.024

23. Rubin O.D., Lisichkin S.E., Zyuzina O.V. Strength of low-reinforced concrete structures with the inter-block construction joints reinforced by prestressed basalt-composite bars. *Prirodoobustrojstvo*. 2021;V(1):53–62. https://doi.org/10.26897/1997-6011-2021-1-53-62 – EDN: ZHAYMH. (in Russian)

24. SP 295.1325800.2017. Concrete structures reinforced with polymer composite reinforcement. Design rules. M: *Standardinform*. 2017; 55. (in Russian)

ADDITIONAL INFORMATION

The authors state that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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CONTRIBUTION OF THE AUTHORS

Oleg D. Rubin – scientific supervision; development of the concept and development of research methodology; analysis of research results; writing the text of the article; drawing up final conclusions.

Anton S. Antonov – conducting experimental work; processing and analysis of experimental data using machine learning methods; writing the text of the article; drawing up final conclusions.

Amer Almasri – literature review; collection and systematization of experimental data; writing the text of the article.

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