

## DESIGN AND EXPERIMENTAL STUDIES OF STRENGTHENING OF BACKWATER TYPE HYDRAULIC STRUCTURES WITH COMPOSITE MATERIALS

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**Abstract:** During long-term operation of hydraulic structures of sluices, retaining walls, abutments, there are non-design settlements, tilts, displacements, opening of inter-block construction joints, corrosion of working reinforcement, change in strength characteristics of concrete, which leads to a decrease in operational properties and bearing capacity. The analysis of scientific and technical documentation is presented, the results of surveys are analysed, a spatial mathematical model based on the finite element method is developed. The computational research of the stress-strain state of sluices is carried out, including taking into account the reinforcement with prestressed basalt-composite reinforcement. The scheme of reinforcement of sluice walls has been justified by calculation. In experimental researches the complex problem on definition of strength, deflections, width of opening of inter-block construction joints, deformations of steel and prestressed basalt-composite reinforcement of reinforced concrete structures including those exposed to water environment was solved. The conducted design and experimental studies substantiate the use of prestressed basalt-composite reinforcement as an effective method of reinforcement of retaining structures, increasing their load-bearing capacity and maintaining deflections, width of opening of interlock construction joints, deformations of steel and prestressed basalt-composite reinforcement within the limits allowed by normative documents.

**Keywords:** sluice walls, design and experimental studies, inter-bay construction joints, cracks, reinforcement, prestressing, basalt-composite reinforcement, transverse reinforcement, bearing capacity

## РАСЧЕТНО-ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ УСИЛЕНИЯ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ ПОДПОРНОГО ТИПА КОМПОЗИТНЫМИ МАТЕРИАЛАМИ

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**Аннотация:** При длительной эксплуатации гидротехнических сооружений шлюзов, подпорных стен, устоев возникают не проектные осадки, крены, перемещения, раскрытие межблочных строительных швов, коррозия рабочей арматуры, изменение прочностных характеристик бетона, что приводит к снижению эксплуатационных свойств и несущей способности. Представлен анализ научно-технической документации, проанализированы результаты обследований, разработана пространственная математическая модель на основе метода конечных элементов. Проведены расчетные исследования напряженно-деформированного состояния шлюзов, в том числе с учетом усиления предварительно напряженной базальтокомпозитной арматурой. Обоснована расчетным путем схема усиления стен шлюзов. В экспериментальных исследованиях решалась комплексная задача по определению прочности, прогибов, ширины раскрытия межблочных строительных швов, деформаций стальной и предварительно напряженной базальтокомпозитной арматуры усиления железобетонных конструкций, в том числе подвергшихся воздействию водной среды. Проведенные расчетно-экспериментальные исследования обосновывают применение предварительно напряженной базальтокомпозитной арматуры в качестве эффективного способа усиления сооружений подпорного типа, повышая их несущую способность и сохраняя прогибы, ширину раскрытия межблочных строительных швов, деформации стальной и предварительно напряженной базальтокомпозитной арматуры в допустимых нормативными документами пределах.

**Ключевые слова:** стены шлюзов, расчетные и экспериментальные исследования, межблочные строительные швы, трещины, усиление, предварительное напряжение, базальтокомпозитная арматура, поперечное армирование, несущая способность

## INTRODUCTION

The methodology of computational-experimental studies of strengthening with prestressed basalt composite reinforcement (BCR) of sluice chamber walls taking into account the actual data on the operational condition is based on finite element models of the system "structures - surrounding soil mass - base" and data of experimental studies [1-14].

Bending studies of reinforced concrete beams with basalt reinforcement (BFRP) [1] indicate that the use of BFRP is an effective way to repair and strengthen structures that have changed their performance characteristics over a period of long-term operation. BFRP repair systems provide a cost-effective alternative to conventional repair systems and materials. It is noted that BFRP reinforcement has high tensile strength and a lower modulus of elasticity than steel reinforcement. The advantages of BFRP over steel reinforcement are also noted.

It is noted that BFRP is an ideal choice for use in buildings and structures operating in water environments, including marine environments; BFRP increases the service life of reinforced concrete structures, resulting in long-term safe operation of structures.

The paper [2] presents the results of experiments in bending of prestressed beams reinforced with BFRP, including the evaluation of prestress losses. Five beams were fabricated, of which three were reinforced with 6 mm diameter BFRP prestressed to 20%, 30% and 40% of the ultimate prestress level. The prestress losses were monitored using strain gauges on the reinforcement bars. In addition, two control beams were reinforced with tensile BFRP and steel bars of the same cross-sectional area, respectively. The dimensions of all specimens were 125x200x1900 mm.

Based on the results of experiments with beams tested in bending to failure, the following conclusions are presented:

- prestressing more than 30% (of the ultimate tensile strength of the bars) of the BFRP-reinforced beams improved the performance of

the beams to a level exceeding that of the steel bar-reinforced specimens;

- the ultimate deflections of prestressed beams are recorded lower compared to unstressed beams with BFRP;

- the crack opening at different values of prestressing of reinforcement bars was measured.

It should be noted that the conducted studies do not contain data on strengthening of the beams with external reinforcement system.

The aim of the research [3] was to study the flexural strength of beams reinforced with NSM (near surface mounted) technology using basalt-composite reinforcement (BFRP), and to evaluate the effectiveness of the strengthening. In addition, the near surface mounted prestressing technology (PNSM), which to some extent combines two well-known technologies "external prestressing" and "NSM", was considered.

The variables considered in this study were:

- strengthening effect (not strengthened and strengthened);

- type of composite reinforcement (BFRP and GFRP);

- strengthening method (NSM and PNSM);

- initial prestress level (30% and 50% of the ultimate tensile strength of BFRP bars);

- position of the NSM composite reinforcement (bottom and side).

The test results demonstrated the effectiveness of using BFRP beams for NSM and PNSM strengthening of RC beams. In addition, BFRP reinforcement provided an additional advantage over GFRP reinforcement for PNSM strengthening due to its higher tensile and deformation strength.

In the article [4] the options of basalt composite reinforcement (BFRP) application for strengthening of RC-beams were considered and according to the research results the conclusion was made: since BFRP have much lower bending stiffness than traditional steel reinforcement, it is necessary to use BFRP prestressing to maintain beam deflections within acceptable values.

This paper focuses on the evaluation of the failure and shear behaviour of concrete beams

reinforced with prestressed BFRP in the absence of reinforcement clamps. Both experimental and numerical results (ANSYS) are presented in the paper. All tested beams showed identical failure mechanics: bending and shear. As it follows from the article, the experimental results and results obtained by numerical modelling in ANSYS are in reasonably good agreement. Thus, the research results are very useful for the development of strengthening systems for serviceable reinforced concrete structures.

In [5] the results of experimental studies of concrete beams with prestressed reinforcement are presented.

The experimental results were analysed, computational nonlinear models were created in ANSYS and a fairly good agreement between experiments and calculations was obtained in terms of the nature of fracture and numerical values of the failure load, as well as in terms of stress distribution.

The article [6] analyses the results of tests of concrete beams with prestressed basalt composite reinforcement, including those with and without external clamps. It is noted that the use of concrete beams with steel reinforcement is problematic when exposed to water and saline environments, as well as chemicals due to intensive corrosion, and therefore the use of BFRP reinforcement is necessary. In order to prevent intensive cracking in the beams it is necessary to pre-stress the BFRP reinforcement. Experiments were carried out on two beams with shear failure. The other two beams were shear reinforced with external steel clamps and collapsed in bending due to yielding of the reinforcement. In summary, it is noted that the distribution of shear force and bending moment along the length of the beam must be considered in the design of beams in order to create structures of the required strength.

It is noted in [7] that BFRP reinforcement is a new environmentally friendly construction material. In this study, the performance of concrete beams reinforced with BFRP reinforcement was evaluated. Full-scale tests were conducted on eight large-scale specimens of concrete beams reinforced with either BFRP

reinforcement or steel reinforcement. The test data were analysed to evaluate the shear and flexural performance of concrete beams reinforced with BFRP reinforcement. It was found that at low reinforcement ratio, beams reinforced with BFRP reinforcement exhibited more flexural and shear cracks than similar beams reinforced with steel reinforcement. Cracking moments were found to be 30-50% higher for specimens reinforced with steel reinforcement compared to specimens reinforced with BFRP. The study also showed that shear failure can be determined by the design of reinforced concrete beams reinforced with BFRP reinforcement and containing BFRP clamps.

The paper [8] investigates the shear strengthening of flat slabs using carbon fibre reinforced polymer (CFRP) sheets. Fifteen reinforced concrete slab specimens were tested. Thirteen of them were reinforced with CFRP sheets and two specimens were left as control specimens. Four reinforced specimens were tested by cyclic vertical loading. The width of the CFRP sheets varied from specimen to specimen. The CFRP sheets were placed on the tensile side of the plates in two perpendicular directions. The vertical load was applied using a hydraulic jack. No rupture of the CFRP sheets was observed in all specimens. The test results showed that the use of CFRP sheets in addition to steel reinforcing bars as flexural reinforcement improves the pushover shear strength of the slabs. This improvement can be significant for slabs made of high-strength concrete with low steel reinforcement ratio. However, under cyclic vertical loading, the improvement in pushover shear strength due to FRP reinforcement is reduced. For strengthened slabs, the equivalent reinforcement coefficient should be used to account for the effect of both steel and FRP reinforcement on the flexural resistance.

The research [9] presents a method of mounting reinforcement near the surface (NSM), which is one of the promising methods currently used for strengthening of reinforced concrete structures. In the NSM method, carbon fibre reinforced polymer (CFRP) bars are placed in pre-cut grooves and attached to concrete with epoxy

adhesive. In this paper, corroded beams repaired by NSM technique using CFRP rods are investigated. The failure mode of the repaired beam is studied by experimental and numerical modelling results. Experimental results and numerical simulation results with a two-dimensional finite element model using FEMIX software were obtained on five 3 m long beams: three corroded beams that had been subjected to natural corrosion for 25 years and two control beams without corrosion. Two beams, one corroded and one control beam (A1CL3-R and A1T-R), were flexural strengthened using the NSM method with a single 6 mm diameter CFRP rod and then tested in three-point bending until failure. The ultimate strength, yield strength and failure modes were analysed. Experimental results showed that the NSM method increased the overall strength and yield strength of the control and corroded beams, despite the non-classical failure mode with delamination of the concrete cover in the corroded beam due to corrosion damage. The results of the numerical simulations in FEMIX were in agreement with the experimental results. Comparisons were made between the experimental results and the numerical simulation results obtained using ABAQUS software to investigate the specific failure mode of the corroded beam that occurred as a result of concrete cover separation.

In [10], an innovative hybrid reinforcement is investigated to improve the strength of reinforced concrete flexural elements. The main objective of this study is to evaluate the effectiveness of hybrid fibre reinforced polymer (FRP) strengthening in the overall evaluation of the flexural behaviour of reinforced concrete (RC) elements. Eight full-scale square RC elements were moulded and strengthened with FRP using a variety of techniques including near surface mounted (NSM) FRP carbon laminates only, externally bonded (EB) carbon fibre reinforcement only and hybrid strengthening using a combination of NSM carbon fibre reinforcement and EB carbon fibre fabric. A three-dimensional non-linear finite

element (FE) based model is developed to simulate the behaviour of RC beams with and without FRP reinforcement. Experimental results showed that the hybrid FRP strengthening is able to increase the strength by 175% compared to the control RC specimens. RC beams strengthened by NSM method alone increased the maximum strength by 111%.

Paper [11] presents a study of lightweight, non-corrosive basalt composite reinforcement bars (BCR) made of continuous basalt filaments, epoxy and polyester resins by pultrusion. It is a rod with a continuous spiral ribbing formed by basalt filament for better bonding with concrete. The advantages of BCR reinforcement compared to steel reinforcement are presented:

- BCR is more than twice as strong in tension (to prevent cracking in concrete) as steel reinforcement;
- BCR is not susceptible to corrosion, which is inherent to steel reinforcement;
- BCR is 89 % lighter than steel reinforcement (significantly faster fabrication, installation and handling of BCR);
- BCR has the same coefficient of thermal expansion as concrete;
- basalt fibres do not absorb or transmit moisture and therefore do not create water penetration pathways that cause concrete failure;
- BCR is not a conductor of electricity, which prevents electrolysis in marine environments;
- BCR does not create magnetic fields when exposed to electromagnetic energy;
- BCR operating temperature range from  $-70\text{ }^{\circ}\text{C}$  to  $+100\text{ }^{\circ}\text{C}$ , which is an important parameter for operation also in fire-resistant rooms.

Thus, the use of basalt-composite reinforcement increases the service life of reinforced concrete structures, which is relevant in the creation of long-term operating structures, which include the structures of hydroelectric power plants.

In the article [12] it is noted that nowadays the method of strengthening of reinforced concrete structures of long-term operating hydraulic structures by the system of external reinforcement based on carbon fibre fabrics is being applied. At

the same time, the specified method of strengthening is applicable for structures, to the tensile zone of which there is an access.

In headwalls, abutments, sluice walls and other hydraulic structures on the side of the tensile face there is a soil backfill for practically their entire height, which essentially excludes the use of external strengthening.

The application of prestressed basalt-compact reinforcement for strengthening of operating reinforced concrete structures with installation and caulking in drilled boreholes seems to be effective. Experiments of reinforced concrete fragments reinforced with BCR have shown an increase in strength up to 1.55 times. Practical recommendations on the placement of prestressed BCR in structural sections based on experimental and design studies are presented.

The research [13] is experimental and theoretical and is aimed at developing a methodology for numerical modelling and calculation of reinforced concrete structures of operating hydraulic structures strengthened with prestressed basalt-composite reinforcement.

Vertical inter-bay construction joints, normal and inclined cracks, steel and basalt-compact reinforcement were reproduced in spatial finite element models. Comparison of experimental values of stresses in the compressed zone of concrete structures, tensile stresses in prestressed BCR and in steel reinforcement, width of opening of inter-bay joints and cracks with calculations confirms the operability and reliability of the developed method of modelling and calculation of reinforced concrete structures of operating hydraulic structures strengthened with prestressed BCR.

The paper [14] analyses the results of inspection of sluice wall structures, develops a spatial model based on the finite element method, and performs calculations to determine the stress-strain state, including strengthening with prestressed basalt-compact reinforcement. As a result of the calculations, the occurrence of cracks and opening of horizontal construction joints were confirmed. At the same time, taking into account the corrosion of reinforcement in the area of

construction joints established by inspections, tensile stresses occur in it, reaching the design resistance of A-II class reinforcement.

During the repair of sluice walls the anchorage of "new" concrete with "old" concrete was investigated and found to be insufficient in terms of anchorage length. It is noted that repair of sluice walls from the side of the front face plays mainly the role of preservation of concrete of the main mass and restoration of concrete parameters in the compressed zone (from the side of the front face), while the work of the wall structure as a whole and first of all from the side of the back surface (from the side of soil backfill) is unsecured. Justification of application of prestressed BCR for strengthening of sluice walls with placement at the faces and back surfaces of the walls with reduction of tensile stresses by 40 % in the steel rear reinforcement installed during the construction period is given, thus reducing the width of crack opening along the construction joints, providing extension of service life of the structure as a whole.

Thus, researches [1-14], aimed at substantiation of the technology of strengthening of operating reinforced concrete structures by means of application of perspective composite materials, require further development and improvement in relation to various reinforced concrete structures having high safety requirements.

## METHODS

Strengthening of structures based on the use of prestressed BCR allows to increase the load-bearing capacity of structures. The choice of BCR is justified by the following:

- The cost of BCR is comparable in value to steel reinforcement;
- BCR has 2.5-3 times higher tensile strength compared to steel reinforcement with equal diameter;
- BCR is resistant to the alkaline environment of concrete;
- BCR weight compared to steel reinforcement is 4-4.5 times less with the same diameter;

– BCR corrosion resistance (does not corrode in water, moisture saturated and aggressive environments).

Also of note is the use of an integrated strengthening method: BCR and composite external reinforcement with carbon tapes.

Corrosion of steel reinforcement is inevitable in reinforced concrete structures during operation of hydraulic structures. Therefore, the use of BCR reinforcement seems reasonable in solving this problem when strengthening structures.

Application of the finite element method is widely spread for establishing the actual condition of stress-strain state of hydraulic structures (HS). With the modern development of computational technology, it is possible to solve nonlinear problems and determine by calculation the actual location and opening of cracks and inter-bay construction joints in structures.

## RESULTS AND DISCUSSION

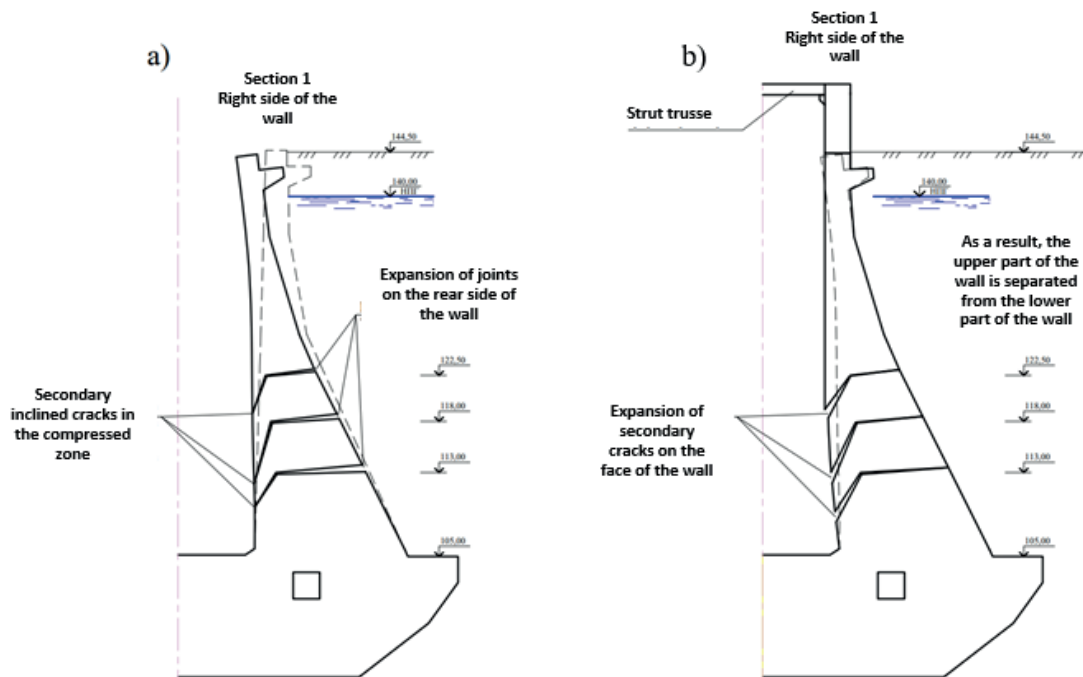
Initial data for design and experimental studies of sluice walls on the example of Pavlovsk and Gorodets sluices (Russia):

1. The Pavlovsk sluice is a single lift, single-line sluice made of monolithic reinforced concrete. Overall dimensions of the sluice chamber: length - 120.0 m; width - 15.0 m; wall height - 39.5 m.

The sluice chamber consists of 4 sections.

A distinctive feature of the condition of the walls of the sluice chamber before the overhaul in 2022 - 2023 was the presence of horizontal cracks on the face of the lower wall, which represent the exit of secondary inclined cracks (Fig. 1), wedged out of the horizontal inter-bay construction joints in the direction of the face side due to the lack of transverse (horizontal) reinforcement in the wall. There were also voids in the concrete going deep into the wall mass along the path of inclined cracks (Fig. 2).

2. Composition of navigable structures of the Gorodets hydro-scheme: two lines of single-chamber reinforced concrete sluices. Overall dimensions of the sluices' chambers: length - 290.0 m; width - 30.0 m; wall height - 14.0 m. Each sluice chamber consists of 12 sections.



*Figure 1. Nature of formation and opening of secondary inclined cracks*

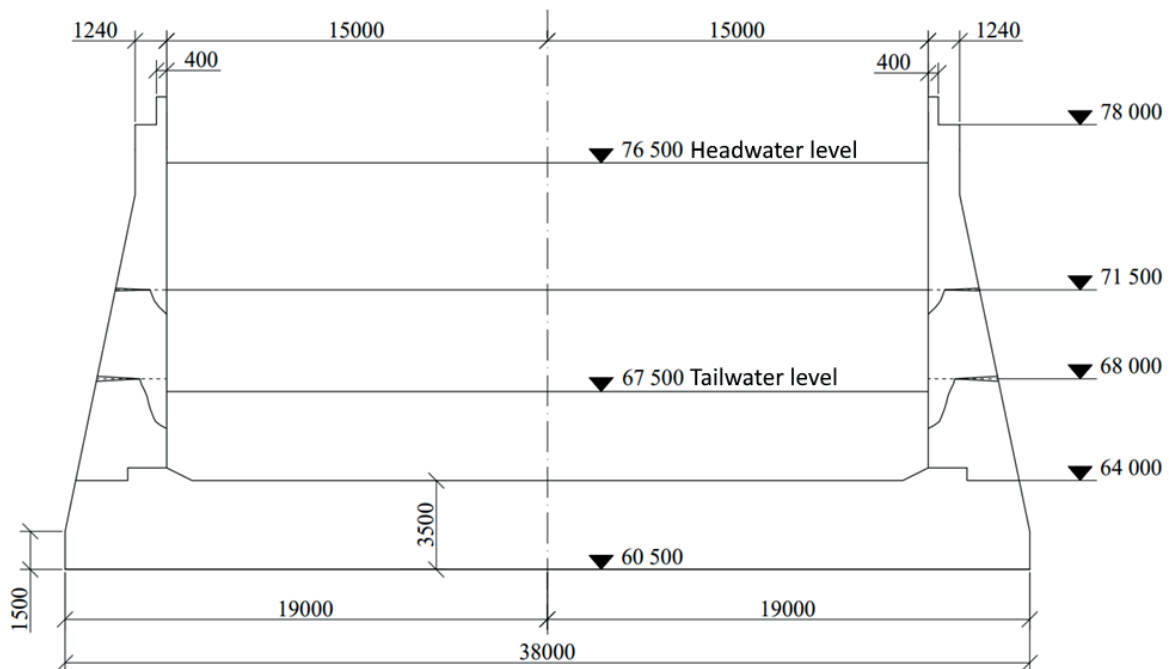
Inspections carried out prior to the overhaul (2017-2018) of the sluice chamber walls revealed the presence of multidirectional cracks and, primarily, outcrops on the faces of secondary inclined cracks (Fig. 3) formed from inter-bay construction joints, as well as voids extending deep into the concrete mass of the walls (Fig. 4) along the path of inclined cracks.

**DESIGN CASE**

Based on the analysis of various load combinations during operation and overhaul of sluice chambers, as well as on the analysis of design materials and the results of earlier studies, the design case corresponding to the most unfavourable state of loading of sluice chamber walls is accepted:



*Figure 2. View of the right wall of section No.1 with a sloping crack extending to the face, with voids, exposed reinforcement and water leaks (before overhaul)*



*Figure 3. Section of the sluice chamber. Dimensions are given in mm, marks in m*



*Figure 4. View of a wall with sloping cracks extending to the face, with voids, exposed reinforcement and water leaks (before overhaul)*

1. In the case of a drained chamber, the load from the ground pressure on the rear edge of the wall is the highest and the groundwater level is the highest (in the case of rapid emptying of the chamber, when the water level in the ground behind the wall does not have time to drop).
2. The impact of winter temperatures is taken into account.

#### **METHODOLOGY OF COMPUTATIONAL MODELLING AND EXPERIMENTAL STUDIES OF REINFORCED CONCRETE STRUCTURES**

The present method provides finite element modelling of sluice structures as part of the system "structure - backfill - base" in a spatial setting, as the sluice chambers and heads, as well as their backfill interact with each other. Experience in numerical modelling of HS

reinforced concrete structures with construction joints has been taken into account in the development of the methodology.

Finite element models take into account the structural features of the structures, including the actual placement of reinforcement. Horizontal and vertical contact construction joints are modelled, taking into account the strength reduction under the combined action of shear with tension or compression compared to a continuous monolithic structure. Breach of bond between reinforcement and concrete in the zones of opened horizontal construction joints and cracks is modelled.

Special approaches are used for modelling cracking of construction joints and monolithic concrete, as well as cracking of face concrete. In this case, the conditions for crack formation are the action of tensile stresses exceeding the tensile strength of concrete and the strength of joints in a complex stress state, i.e. the combined action of shear forces with tensile (or compressive) forces in the plane of construction joints.

In the calculation model, horizontal and vertical construction joints caused by interruptions in the concreting of the walls and repair of the concrete face were specified. In the areas of construction joints, the disruption of bonding of the working reinforcement in the concrete of the sluice walls during the construction period was taken into account.

Due to cracking of the face concrete, a reduced strain modulus is taken into account in the calculation models.

Also, the calculation models take into account the corrosion deterioration of the working reinforcement of the back surface of the wall as a result of a long period of operation.

The model of the system "structure - backfill - base" reproduced a fragment of the sluice base massif, massifs of soils of the backfill of the slots behind the outer walls of the chambers and the backfill of the inter-sluice space (between the inner neighbouring walls of the two lines of sluices).

Loads are modelled in accordance with the accepted design scheme (i.e. in accordance with

the accepted levels of soil, groundwater, water in the chambers, etc.), as well as taking into account physical and mechanical properties of materials of structures, base soils and backfills. The main and auxiliary software were used for calculation studies allow obtaining loads on sluice structures from soil and water taking into account the current state of soil mechanics theory (reflecting the peculiarities of soil pressure as active, reactive, passive, at rest, etc.).

Temperature effects were reproduced in the models "structure - backfill - base" in accordance with average monthly and average annual temperature values for the area of hydraulic structures on the basis of normative documents. The thermophysical properties of the areas of the "structure - backfill - base" system were also taken into account.

The problem of temperature distribution inside the computational domain was solved in one of the modules of the computational software system. Initial design temperature values were set on the contour of the computational domain and then, taking into account the thermophysical properties of the elements of the domain, the temperature values inside the domain were calculated.

In accordance with the obtained temperature distribution in each finite element into which the computational domain is divided, the main problem of determining the deformed and then the stress state of the structure was solved.

One of the most important features of the approach of modelling structures, which distinguishes it from traditional approaches to ordinary engineering calculations to be used in design, is that it allows various damages, defects and other deviations from the assumptions adopted in design to be taken into account by incorporating them into the finite element models being developed and adjusted.

In the experimental studies, a complex problem was solved to determine the strength, deflections, opening width of inter-bay construction joints, deformations of metal and prestressed basalt composite reinforcement

(BCR) of strengthened reinforced concrete structure.

Phasing of the work:

- experimental studies of low-reinforced RC models (analogues of hydraulic structures, for example, sluice walls, retaining walls, hydroelectric power plant piers) with operational cracks (including inter-bay construction joints) reinforced with metal reinforcement and BCR strengthening;

- experimental studies under static loading of reinforced concrete models strengthened with transverse reinforcement in the zone of inter-bay construction joints (in the zone of joint action of bending moments and transverse forces);

- experimental research of reinforced concrete models strengthened with composite straps in the zone of joint action of excessive moments and transverse forces, under the action of static loading, and repeated research after holding for 60 days in a water environment.

Reinforced concrete models (2020) are used:

- 1) concrete of class B30-B35;

- 2) metal reinforcement A400;

- 3) basalt-composite reinforcement ( $R_{f\mu}=800$  MPa and  $E_{f\mu}=50\ 000$  MPa);

- 4) *Carbon Wrap Tape* with a surface density of  $(900\pm30)$  g/m<sup>2</sup> and *Carbon Wrap Resin* epoxy two-component binder.

Computational studies of the Pavlovsk sluice walls taking into account the formation and opening of cracks along the inter-bay construction joints revealed the trajectories of inclined secondary cracks (Fig. 1.a). For example, tensile (horizontal) stresses of 4.2 MPa were obtained in the right wall of section No.1 in the joint zone at 118.00 m and 4.9 MPa in the left wall, which is significantly higher than the tensile strength of the wall concrete.

The obtained values of tensile stresses confirm the formation of secondary inclined cracks wedging out of the inter-bay construction joints, with the exit to the face of the walls. The calculations also show that the stresses in the transverse (horizontal)

reinforcement in the zones of secondary inclined cracks significantly exceed the resistance of transverse reinforcement of A-I class ( $R_{sw} = 175 \text{ MPa}$ ). These results indicate an insignificant amount of transverse reinforcement installed solely for constructional (off-design) purposes. The stresses in the longitudinal (vertical) reinforcement at the back surface were obtained as 304 MPa, which exceeds the resistance of A-I class reinforcement ( $R_s = 225 \text{ MPa}$ ).

In 2022 - 2023, in order to carry out overhaul of the walls face, strut trusses were installed in the upper part of the walls (Fig. 1. b). In this case, the stresses in the transverse (horizontal) reinforcement in the zones of secondary cracks decreased and did not exceed the resistance of transverse reinforcement of A-I class ( $R_{sw} = 175 \text{ MPa}$ ), and the stresses in the longitudinal (vertical) reinforcement at the back surface reached 384 MPa, which exceeds the resistance of reinforcement of A-I class ( $R_s = 225 \text{ MPa}$ ). The stresses in the longitudinal (vertical) reinforcement at the face exceed tensile stresses of 97 MPa.

It should be noted that in this variant with strut trusses, the opening of secondary inclined cracks on the face side was confirmed by inspection results (Fig. 2).

Thus, the calculations of the Pavlovsk sluice walls showed the necessity of their strengthening not only of the face (new concrete and reinforcement, reinforced concrete columns), but also the necessity of reinforcement of the wall structure as a whole through the application of additional prestressed reinforcement.

The computational studies showed (Table. 1) that the maximum displacement of the top of the walls inside the Gorodets sluice chambers, taking into account the corrosion of metal reinforcement of the back surface, was 38.9 mm (1/360 of the wall height) at a stress in the tensile reinforcement of the back surface of the walls - 23.0 MPa, which is close enough (82 %)

to the design resistance for the reinforcement of class A-II (280 MPa), the compression stress in the concrete of the main mass increases up to 7.67 MPa, which exceeds the design compressive resistance for the concrete of class B10 (6 MPa).

In the course of computational studies, cracking in the walls along the contact surfaces of horizontal construction inter-bay joints in the concrete of the main massif was revealed. The presence of tensile stresses in the concreting blocks under the inter-bay joints has been established. In accordance with the provisions of [17] in the structures of the walls of the sluice chambers require horizontal transverse reinforcement in the areas of horizontal inter-bay joints, which was confirmed by calculations.

It should be noted that the face concrete of the sluice walls was replaced with B22.5 concrete in 2017 - 2018 as part of a major overhaul.

It follows from the analysis of the survey results, overhaul measures and a set of calculations that the reconstruction of the face of the Gorodets sluice chamber walls contributed to the preservation of the concrete of the main massif and restoration of the concrete parameters of the compressed zone, while the performance of the structure as a whole and, first of all, on the side of the back tensile surface is insufficiently ensured.

As a result of calculations, it is obtained that the application of prestressed BCR gives the following results:

- installation at the face reduces by 36 % the tensile stresses in the rear metal reinforcement, which is subject to corrosion as a result of prolonged operation;
- installation at the back surface makes it possible to reduce by 42 % the tensile stresses in the rear metal reinforcement, which is subject to corrosion as a result of prolonged operation; reduce the opening width of horizontal construction joints, thus extending the service life of the structure as a whole.

*Table 1. Summary table with the results of calculations*

Type of stress	Both sluice chambers drained	Corrosion deterioration of metal back reinforcement in the opening areas of horizontal construction joints is taken into account	Prestressed BCR at the face is taken into account	Prestressed BCR at the back surface is taken into account
Horizontal displacements of the top of the walls towards the inside of the chamber, mm	31,9	38,9	32,7	31,5
Verticals compressive stresses in the concrete of the main mass, MPa	-4,82	-7,67	-5,49	-5,29
Tensile stresses in the rear metal reinforcement, MPa	164,0	230,0	168,5	161,5

## EXPERIMENTAL RESULTS

In 2020, reinforced concrete beam-type models with vertical inter-bay construction joints and with design dimensions: length - 2000 mm, height - 300 mm, width - 150 mm were manufactured and tested for static loading.

In addition to reinforcing the beams with metal reinforcement, pre-stressed BCR was installed.

In the present research (2024), experiments were carried out on the same experimental beams B1 (with the placement of prestressed BCR in the tensile zone) and B2 (with the placement of prestressed BCR in the compressed zone) in order to obtain new data on the strength, deflections, opening widths of the inter-bay construction joints, stresses in the metal reinforcement and in the BCR after 4

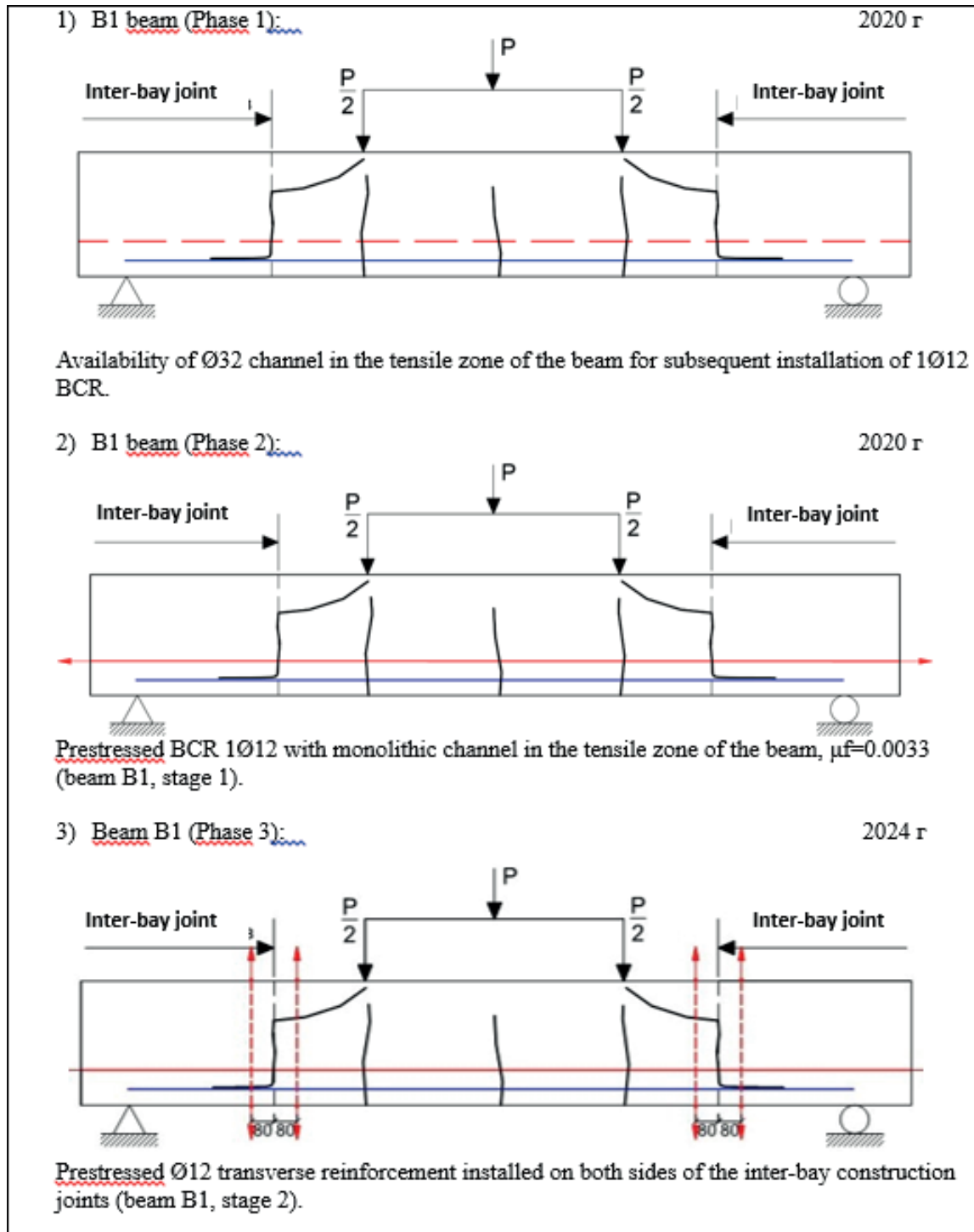
years of prestressing the beams through the application of BCR.

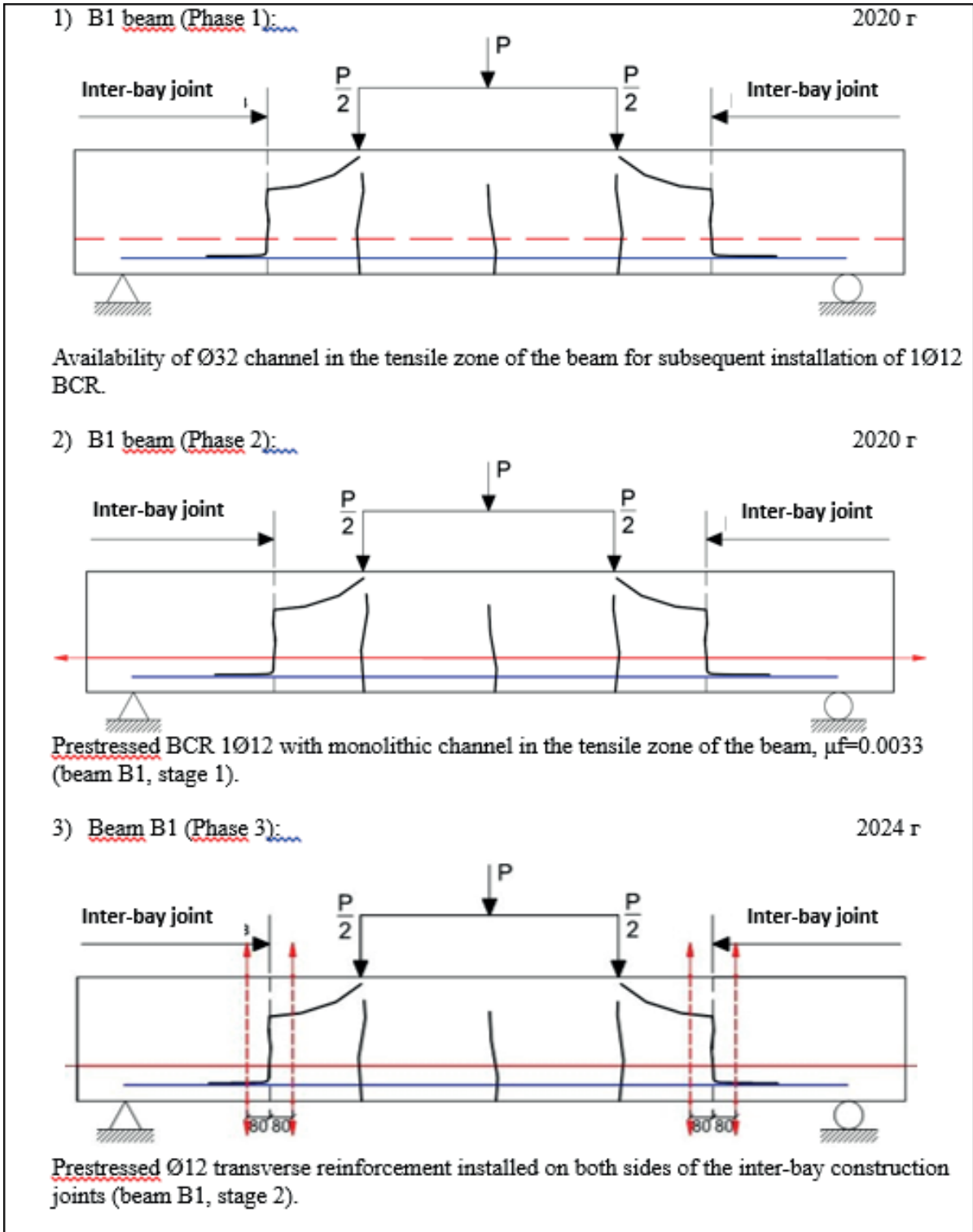
The test type and characteristics of the experimental beams B1 and B2 are presented below. Experimental beams B1 and B2 were fabricated in 2020 with steel reinforcement in two steps (block concreting) for inter-bay construction joints. They had a channel for BCR installation with subsequent prestressing of BCR "on concrete", caulking of the channel and with subsequent release of BCR "on beam concrete" after the channel concrete had gained strength.

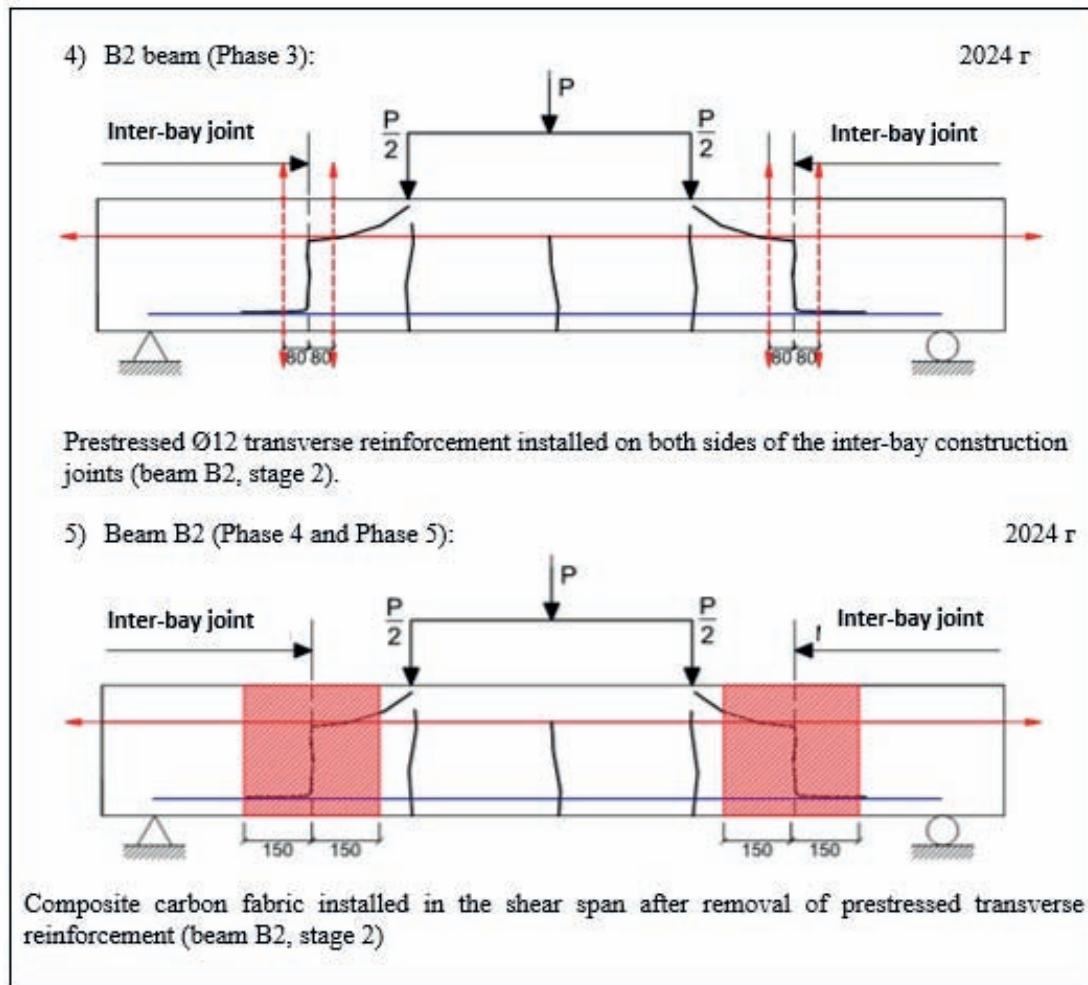
BCR in beams B1 and B2 was subjected to prestressing for the value:  $0.45 \times 800 = 360$  MPa (accepted: coefficient 0.45 regarding [15];  $R_{f,n} = 800$  MPa; BCR tensile strength regarding [16]) with subsequent concreting of channels in the beams.

### Type of testing of test beams

All beams have basic longitudinal reinforcement of  $2\text{Ø}12$  steel reinforcement of class A400 in the tensile zone; longitudinal reinforcement coefficient  $\mu_s=0,0056$ , also all beams have 2 vertical inter-bay construction joints.







It should be noted that  $\text{Ø}12$  transverse prestressed reinforcement was installed in 2024 in beams B1 (stage 3) and B2 (stage 3) on both sides in relation to the inter-bay construction joint; CarbonWrap Tape-900/300 composite fabric in a single layer was bonded in 2024 in the span between the support and the  $P/2$  force application point after removal of the transverse prestressed reinforcement (beams B1 (stage 4) and B2 (stage 4)).

The design of the experimental beams is shown in Figure 5.

It should be noted:

1) During testing, the experimental beams were supported on movable (roller) and fixed (knife) supports located at a distance of 150 mm from the ends.

2) The load was applied vertically in steps by a hydraulic jack and transmitted through a

horizontal crosshead at two points 320 mm from the centre of the beam, with a force spacing (the 'pure bending' zone) of 640 mm and a force-support spacing ('shear span') of 540 mm (Figure 5).

Experimental beams were equipped with instrumentation to measure: deflections; opening width of inter-bay construction joints; deformations of steel reinforcement and BCR. For this purpose, strain gauges with a base of 20-50 mm and clock-type indicators were used. The following main results were obtained in the process of experimental research.

In the experimental beams B1 (stage 1) and B2 (stage 1) in 2020 the following character of cracking was recorded: after opening of vertical inter-bay construction joints there was formation (wedging out) of inclined cracks in the direction to the applied forces  $P/2$  (at the

distance  $X_j = 0,24 \times h_j - 0,34h_j$  from the upper compressed face of the beams) at  $P = 44.2$  kN and 39.0 kN, respectively.

Under the action of a load close to the destructive load, cracks were formed along the longitudinal working reinforcement in the

direction "from the inter-bay joint to the supports" (violation of the bond between the reinforcement and concrete in the tensile zone of the beams). A system of vertical normal cracks was formed at the section between the forces in the "pure bending" zone (Fig. 6).

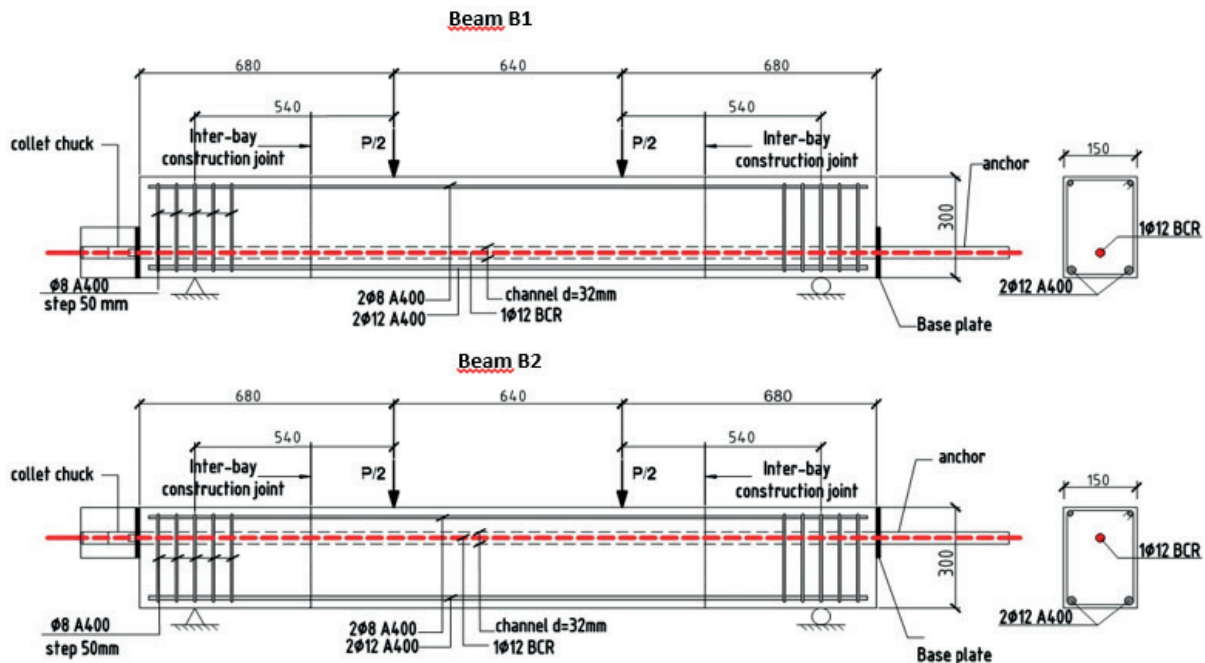


Figure 5. Design of experimental beams B1 and B2

Analyses of the beam test results showed:

- 1) The force corresponding to the failure of not strengthened prestressed BCR beams B1 (Stage 1) and B2 (Stage 1), having working longitudinal steel reinforcement 2Ø12 class A400 in the tensile zone of the beams, in the presence of two inter-bay construction joints, is 46.8 kN and 41.6 kN, respectively. At the same time, in beam B1 (Stage 1) the Ø32 channel for BCR placement is located in the tensile zone and in beam B2 (Stage 1) in the compressed zone, which explains the difference in the magnitude of the failure force. Both the above-mentioned beams failed brittle by an inclined crack formed (wedged) in their inter-bay construction joint from the combined action of bending moment and shear force.
- 2) The tests of beams B1 (Stage 2) and B2 (Stage 2) with prestressed BCR installed in the

tensile and compression zone, respectively, showed that their load carrying capacity increased to 67.6 kN and 55.12 kN, respectively.

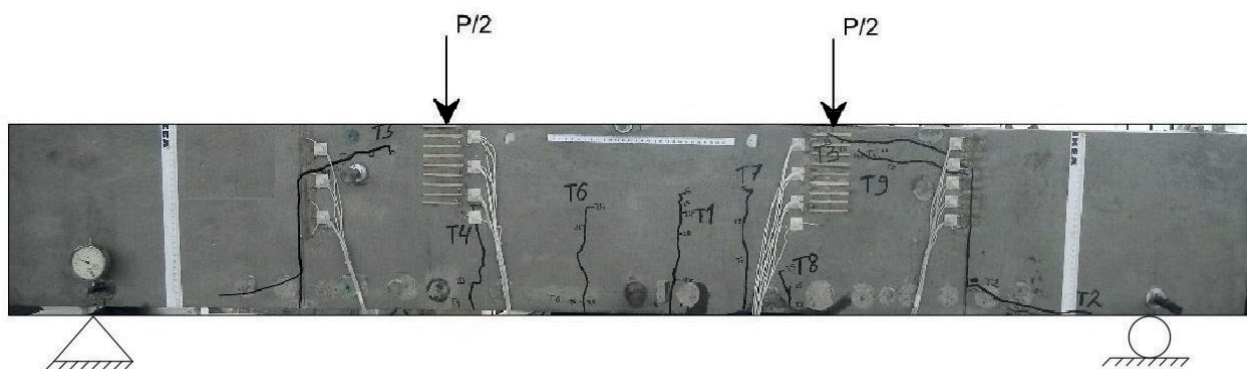
3) Further experiments of beams B1 (Stage 3) and B2 (Stage 3) with prestressed transverse reinforcement up to 50 MPa on both sides of the inter-bay construction joints showed an increase in load carrying capacity up to 83.2 kN with no signs of brittle failure.

4) Further, in the shear span (after removal of transverse reinforcement) of beam B1 (Stage 4), composite fabric was bonded in one layer. The bearing capacity of the beam increased to 142.5 kN with no signs of brittle failure.

After conditioning beam B1 for 60 days in an water environment, the load carrying capacity was maintained at 150 kN with no signs of brittle fracture.

5) In beam B2 (stage 4) after removal of transverse reinforcement, composite fabric was bonded in one layer. The load-bearing capacity of the beam increased to 124.8 kN, while the metal working reinforcement in the tensile zone of the beam was found to yield.

After conditioning beam B2 (stage 5) for 60 days in a water environment, when the load carrying capacity reached 124.8 kN, there were signs of beam failure.



*Figure 6. Cracking behavior in test beams (2020)*

From the analysis of beam test results in terms of deflections, opening width of inter-bay construction joints, deformations of steel and basalt-composite reinforcement it follows:

1) The deflections of beam B1 (stages 1, 2, 3, 4, 5) as it is strengthened from the variant of longitudinal prestressed BCR - location in the tensile zone of the beam (stage 2) - to external transverse reinforcement with composite fabric after exposure in aqueous environment (stage 5) are lower by a factor of 1.32, with deflections of B1 (stage 4) lower than B1 (stage 5) by a factor of 1.14 as a result of the effect of the aqueous environment (Figure 7).

The deflections of beam B2 (stages 1, 2, 3, 4, 5) as it is strengthened from the variant of longitudinal prestressed BCR - located in the compressed zone of the beam (stage 2) - to the external transverse reinforcement with composite fabric are almost the same at  $P=55.12$  kN, with the deflections of B2 (stage 4) lower than B2 (stage 5) by a factor of 1.65, which is the result of the water environment (Fig.8).

It should be noted that the pattern of variation of deflections of B1 and B2 (Figs. 7 and 8) by a smaller magnitude is preferred for B1 with the location of prestressed BCR in the tensile zone

when strengthening by transverse reinforcement with composite fabric.

2) The opening width of the inter-bay construction joints in beam B1 (stage 2) (prestressed BCR located in the tensile zone of the beam) was recorded 1.21 times smaller than that in beam B2 (stage 2) (prestressed BCR located in the compressed zone of the beam) at  $P=55.12$  kN (Figures 9 and 10).

As beams B1 and B2 are strengthened to the options of external transverse reinforcement with composite fabric (stages 4 and 5), the opening width of the inter-bay construction joints varies within 10%, while comparison with the normative document [17] shows that the permissible values are not exceeded  $a_{cr,i}$  (Fig. 8 and 9). It is noted that in the research variant B2 (stage 5) in comparison with B2 (stage 4) the width of opening of inter-bay construction joints is on average 1.23 times higher (Fig. 9).

3) Strengthening of beams B1 and B2 (steps 3) with external prestressed transverse reinforcement resulted in increased deformations of steel reinforcement (Figures 11 and 12). 3) Strengthening of beams B1 and B2 (steps 4) with external transverse reinforcement with composite fabric reduced the deformations of the steel reinforcement, while

the deformations of the steel reinforcement almost doubled (steps 5) after the beams were aged in a water environment. Comparison  $\epsilon_{si}$  in the study of beams B1 and B2: stages 1, 2, 3 with stages 4, 5 indicates that the option of strengthening by external reinforcement with composite fabric is preferable (Figs. 11 and 12). It should be noted that the maximum tensile strains of steel reinforcement at maximum loads in the range of 83.2-150.0 kN were recorded in the range of  $(160-220) \times 10^{-5}$ , which corresponds to average stresses of 380 MPa close to the yield strength.

4) The tensile strains of the prestressed BCR located in beam B1 (Fig. 12) in the tensile zone showed smaller values (about 2 times) in the strengthening option of external transverse reinforcement with composite fabric (steps 4 and 5).

In inter-bay construction joints, the character of the maximum values of tensile strains of steel reinforcement and prestressed BCR are quite similar (Figs. 11 and 13), indicating their joint operation in the structures.

5) Deformations of prestressed BCR located in beam B2 (Fig.14) in the compressed zone showed compression at all strengthening variants in the range of  $20 \div 75$  MPa.

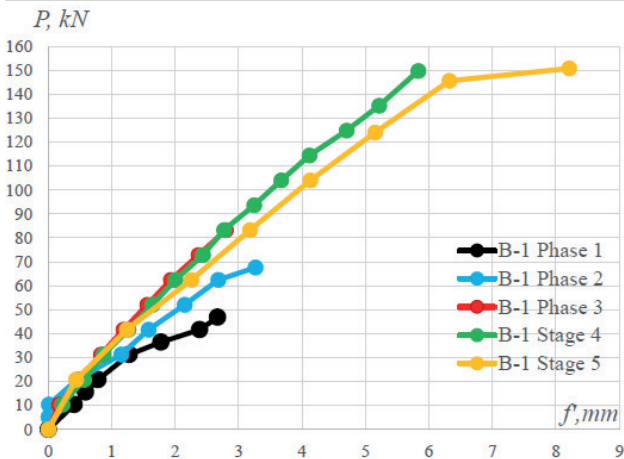


Figure 7. Deflection diagram of beam B1

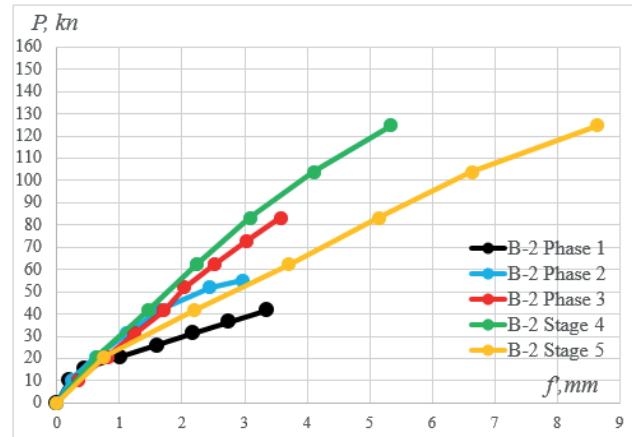


Figure 8. Deflection diagram of beam B2

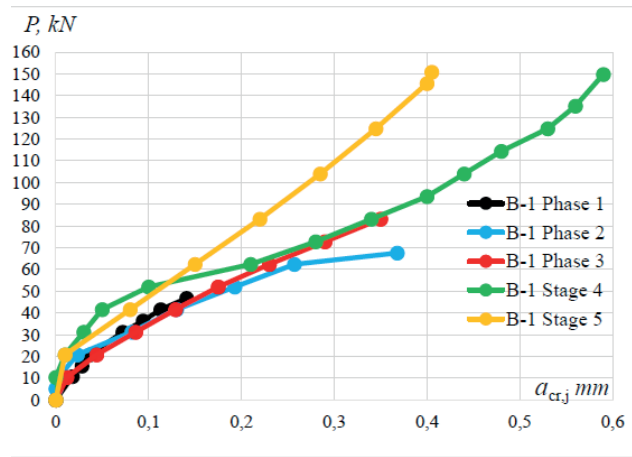


Figure 9. Diagram of opening widths of inter-bay construction joints in beam B1

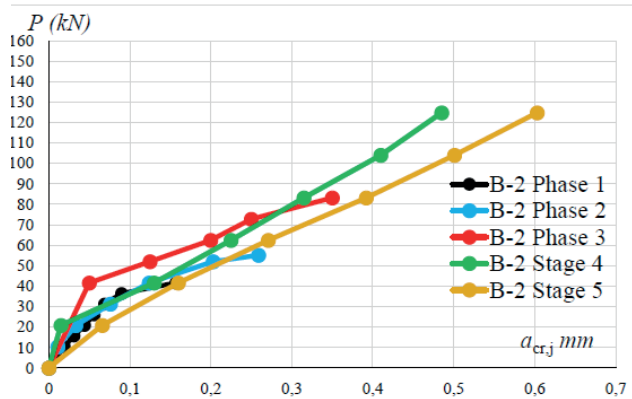


Figure 10. Diagram of opening widths of inter-bay construction joints in beam B2

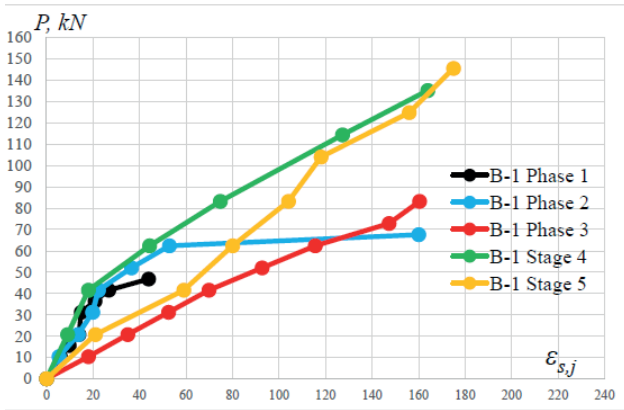


Figure 11. Deformation diagram of steel reinforcement in the joints of beam B1

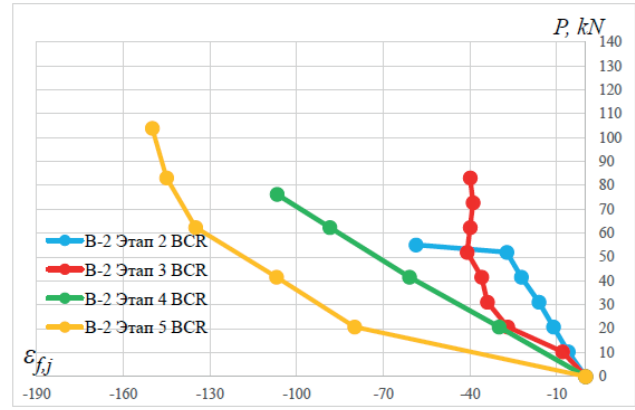


Figure 14. Deformation diagram of prestressed BCR in beam B2

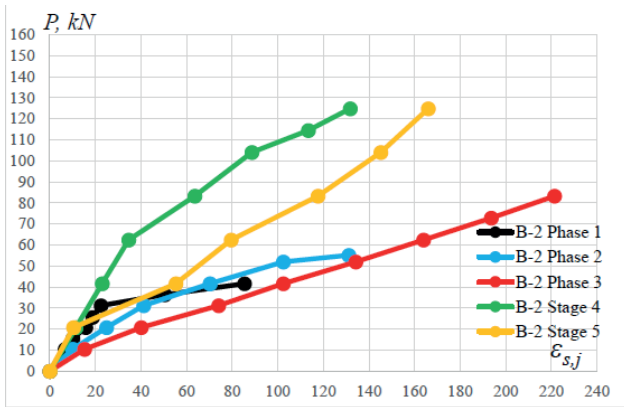


Figure 12. Deformation diagram of steel reinforcement in the joints of beam B2

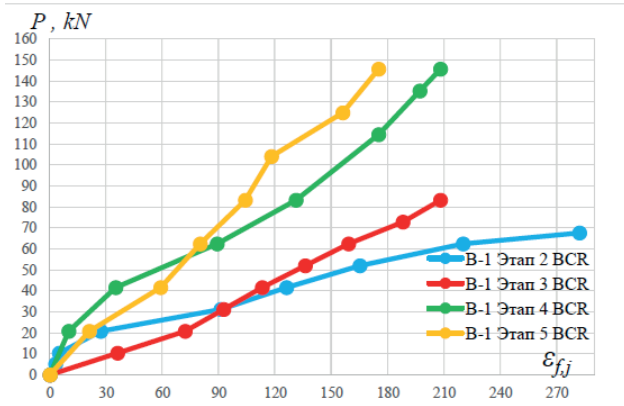


Figure 13. Deformation diagram of prestressed BCR in beam B1

## CONCLUSION

- 1) Experimental studies of low-reinforced concrete beams with cracking (2020) on strengthening with prestressed basalt composite reinforcement and external transverse reinforcement (2024) showed positive results, primarily in that the 4-year conditioning of the beams in prestressed condition (BCR) showed their serviceability and confirmed the stabilisation of prestress losses [18].
- 2) The bearing capacity of beams B1 and B2 increased 1.4 - 2.5 times as they were strengthened from the variant of prestressed basalt-composite longitudinal reinforcement to the variant of external transverse reinforcement, including with holding for 60 days in aqueous environment.
- 3) The deflections of beams, the opening width of inter-bay construction joints, the deformations of steel reinforcement and prestressed basalt-composite reinforcement decrease with the application of various above-mentioned strengthening options. At the same time, the numerical indicators of all values are within the limits allowed by the normative documents [15, 16, 17].
- 4) The fact that in the variant of strengthening with prestressed basalt-composite longitudinal reinforcement located in the compressed zone of the reinforced concrete structure, the load-bearing capacity, deflections, width of opening

of inter-bay construction joints, deformations and stresses in steel longitudinal reinforcement and in BCR are within the limits allowed by the normative documents was very positive.

It follows that in hydraulic structures and structures of hydroelectric power plants, where it is not possible to determine by engineering method the location of the compressed or stretched zone, as well as under the action of seismic impact, the results of research carried out by the authors of the article reasonably allow to achieve a positive effect.

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