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RESEARCH OF GFRP SHELL CONFINED CONCRETE COLUMNS BEHAVIOR UNDER AXIAL COMPRESSION

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Statement of the problem. The influence of external GFRP (glass-fiber-reinforced-plastic) shell, with different physicomechanical longitudinal and transverse properties on increasing the strength of the concrete core is investigated.
Results. The article presents the results of experimental investigations of the load-bearing capacity to evaluate the effectiveness of using a solid fiberglass outer shell as a reinforcement of a concrete column. The results of the study has allowed us to establish the major factor that significantly affects the load-bearing capacity of a hybrid column with a composite shell.
Conclusions. A higher load-bearing capacity of hybrid supports in comparison with the concrete columns traditionally used in bridge construction. This proves the possibility of using hybrid columns in the supports of bridge structures consisting of concrete core confined solid fiberglass outer shell that were not previously used in bridge structures.

Keywords: experimental investigations, reinforced concrete bridge supports, support pillars of bridges, composite materials, fiberglass shells, hybrid structures.

Introduction. Bridge support structures mostly made of reinforced concrete are currently subjected to increased loads, which is due to the development of vehicles, growing intensity of traffic flow and car loads. There is thus a need to boost the load-bearing capacity of bridge structure supports. At the same time, structures of reinforced concrete bridge supports are negatively impacted by an operating environment (aggressive atmospheric gases, high air humidity, dissolved minerals, anti-icing materials, etc.). This is where concrete destruction processes take place at an intensive rate considerably reducing the durability and reliability of structures resulting in limited operation of these structures and the need to restore them. At the same time, composite materials are known, particularly fiberglass, made up of glass fibers impregnated with polymer binders. They are not inferior to concrete in regards of strength and rigidity, while having greater durability icompared to the conventionally used concrete and steel [12, 14].

The properties of fiberglass are well combined with reinforced concrete, improving the characteristics of the resulting single hybrid structures. The use of material-hybrid structures of supports where external load-bearing fiberglass elements protect internal reinforced concrete from negative environmental influences, will boost the life cycle and load-bearing capacity of bridge structure supports. The introduction of hybrid structures accommodates the current needs of the bridge industry, therefore the study of their work is a highly relevant task.

As far as the use of new materials is concerned, the study looks only at bridge supports of small and medium-sized overpassesand elevated pedestrian crossings except supports of structures through water barriers or high mountains. In the mentioned bridge structures, post supports with posts (pillars) of circular cross section are employed which are a good fit for the introduction of fiberglass load-bearing outer annular shells. Although in industrial and civil construction, steel-pipe-concrete racks of a similar design are employed in bridge structures, their use is impractical due to a weak resistance of steel to corrosion processes. Despite this the author took the serious experience of testing such structures detailed in the publications of domestic and foreign scientists into consideration, which is indicative of the degree of deve-lopment of this research topic. Experimental studies of steel pipe concrete were performed by A. L. Krishan [6, 8], I. V. Rezvan [15], M. N. Vauchsky [4], S. B. Krylov [9]. Arched bridge structures made of fiber-reinforced pipes filled with concrete were developed by I. V. Ovchinnikov [13]. The joint work of hybrid bridge structures made of fiberglass and concrete was investigated by A. Muc [22]. Repair of bridge posts with composite tapes was explored by S. A. Bokarev [3], Y. Cao [17], K. M. Mosalam [21]. M. El Gawady [18, 19], Y. Wang [23], R. J. Watson [25] tested concrete columns reinforced with steel shells and composite materials.

At the moment, composite materials in bridge structure supports are still in use only during repairs to strengthen the load-bearing structures. There is currently a need to study the specifics of the work of hybrid fiberglass-reinforced concrete structural elements of bridge supports. The objective of the conducted experimental studies was to confirm the possibility of using fiberglass shells as external structural elements of the rack supports of bridge structures.

1. Statement of the objectives of the experimental study, materials used and sample preparation. To meet the objectives of the study, during the planning of tests, the following tasks were set:

— to check the possibility of resistance of fiberglass shells to considerable loads which they must take as part of the structures of the rack supports of bridge structures;

— to investigate the mechanics of work and destruction of fiberglass shells of various manufacturers and types of production;

— to test the theoretical assumption that the limiting factor in hybrid strut compression is the lateral strength of the fiberglass shell;

— to confirm the increase in the strength of the concrete core as part of a hybrid structure with an outer fiberglass shell which is different from the steel shell by varying physical and mechanical properties in the transverse and longitudinal directions. The increase in the strength of concrete in a steel cage has been experimentally proven by scholars in the design of steel-pipe concrete racks [5, 10, 16].

Experimental studies were performed by the author in the research laboratory of mechanical testing of building materials and structures of the St. Petersburg State University of Architecture and Civil Engineering.

Due to a considerable size of the full-scale hybrid rack, model testing of samples was performed. Samples of fiberglass shells had an outer diameter of 100 mm, an average wall thickness of 4 mm, and a height of 1m. In some previous tests [2, 11], struts of low flexibility (0.5 m high with similar shell diameters and thicknesses) were subjected to compression. In this work, for specified dimensions and a height of racks of 1m, the samples have average Euler flexibility. Nevertheless, they should experience the loss of strength earlier than the that of stability, which we set out to verify through the course of experiments.

Three types of fiberglass shell samples were selected for the model experiment. CA-20 brand samples are manufactured using the technology of wet oblique longitudinal-transverse winding. Samples of grades CO-40 and KT-18 were produced by means of the same method, i.e., pultrusion, but had different angles of inclination of glass fibers. This made it possible to consider the features of the encountered composites and the difference in the characteristics of their individual types.

Model samples of the selected fiberglass shells were filled with a specially prepared concrete mix. The concrete mix had the following composition: M500 *Super* eurocement, crushed stone of a fraction of 3...5 mm, polyfractional sand, water, plasticizer "Macromer P-163". The prepared concrete mix was placed in composite shells and thoroughly compacted manually with a metal disc to ensure a tight fit between the concrete and the shell. The edges of the shells on both sides were tightly sealed while the concrete was being cured, and the specimens were kept in this state for more than 28 days. Following that, the samples were visually examined, the absence of defects in the shell and concrete (cracks in these materials, gaps and voids between them) was observed. The compressive strength of the resulting concrete was identified by means of the splitting method using control samples prepared from the concrete mix of the same batch. The resulting prism strength was 36.06 MPa.

During the experiments, using strain gauges, which were installed vertically and horizontally on the outer surfaces of the fiberglass shells of hybrid racks, their longitudinal and tangential relative deformations were measured. Schematic diagrams of their installation sites are shown in Fig. 1.

Strain gauges mounted vertically (numbered 1–4, 9) recorded the longitudinal relative deformations of the shell — $\varepsilon_{к}^{x}$, whereas those located horizontally (numbered 5–8, 10) measured tangential (tangential) relative deformations — $\varepsilon_{к}^{\theta}$. The values of tangential relative strains made it possible to analytically obtain transverse (radial) relative strains — $\varepsilon_{к}^{r}$.

The scheme of directions of flowing relative deformations in the shell is shown in Fig. 2.

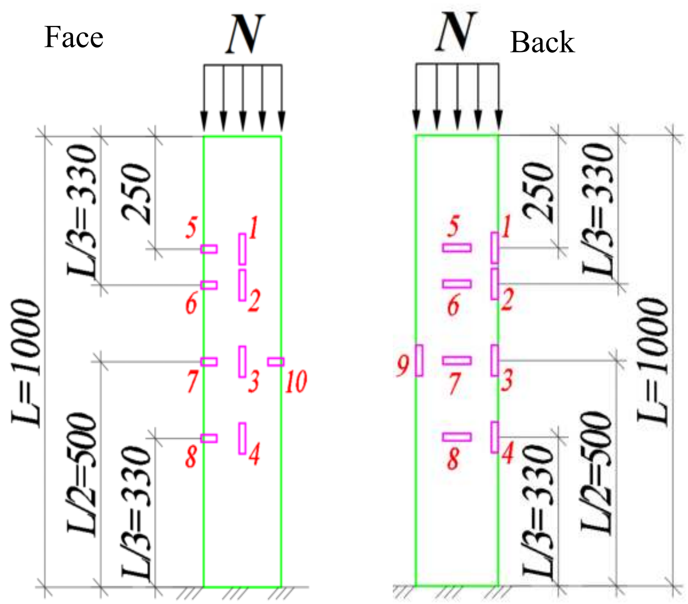

Fig. 1. Measurement of relative deformations: maps of places and directions installation of strain gauges on the samples

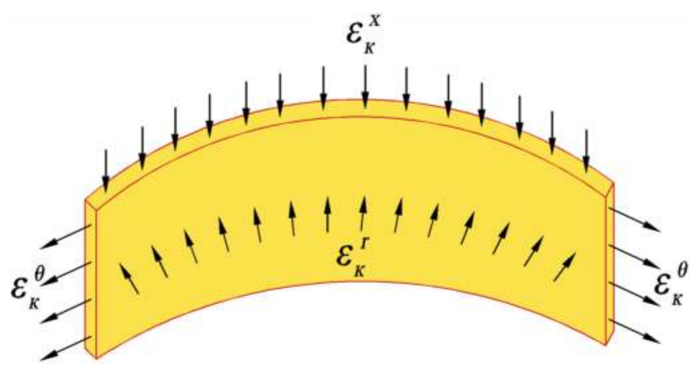

Fig. 2. Measurement of relative deformations: diagram to understanding directions relative deformations of the shell

2. Experimental setup and devices. Program of the experiment. The impact on the samples of compressive load was performed with a universal testing power machine *BISS Magnum UT*-05-2000, which is equipped with a hydraulic drive with fuses and has a maximum force of up to 2000 kN. The experimental data were measured using the *Sokki Kenkyujo Data*

Logger TDS-150 measuring system used in conjunction with thin film strain gauges *PFL*-10-11. This system for measuring local relative deformations made it possible to simultaneously record readings from all measurement points and save records of the results on a PC. The strain gauges were attached to the shells under test with a *CN* series cyanoacrylate adhesive designed for bonding to composite materials. A general view of the unit and devices is shown in Fig. 3. All photographs provided in this article were taken by the author during testing.

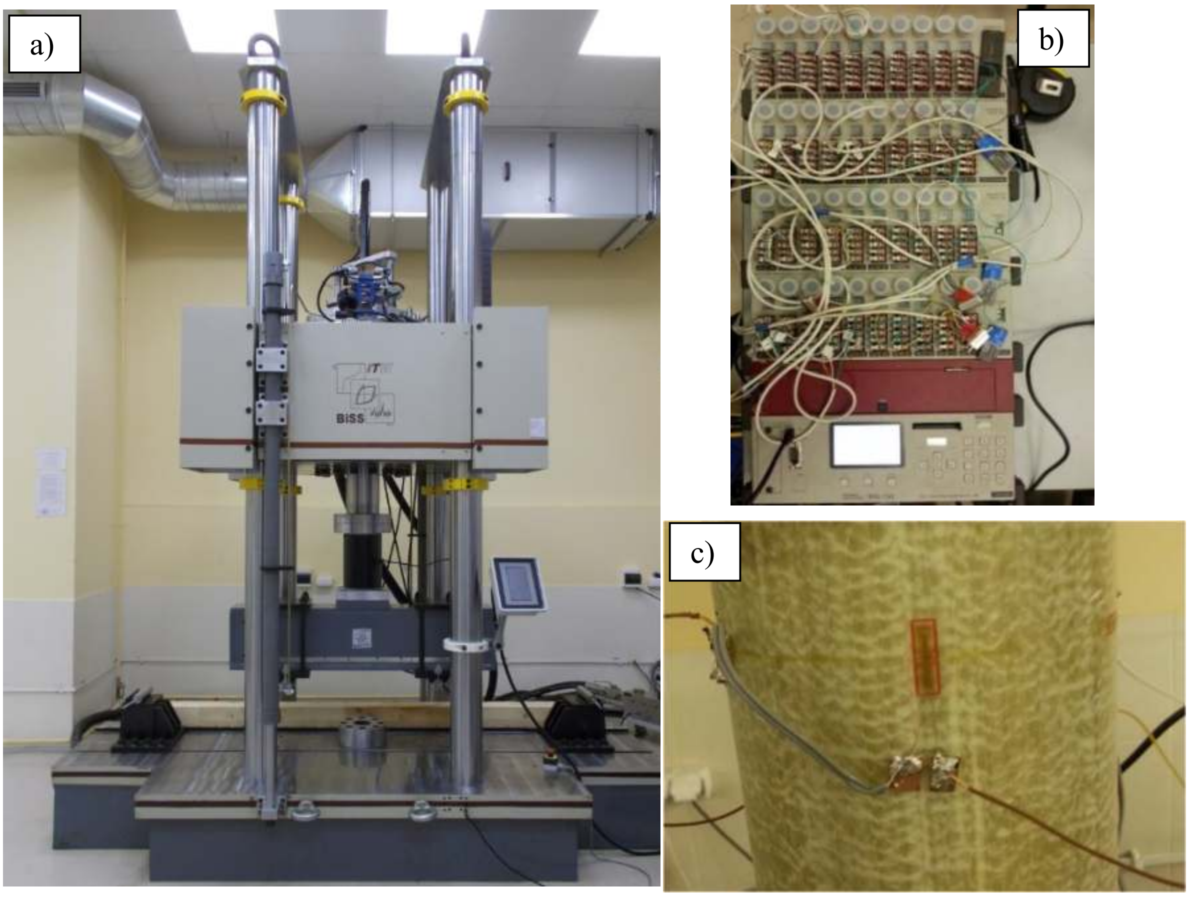

Fig. 3. Applied equipment:
a) general view of the UT-05-2000 power plant; b) base of electronic strain gauge *Data Logger TDS*-150;
c) strain gauge *PFL-10-11* installed on the sample

The impact of the compressive load was performed on the entire section of the hybrid racks — on the concrete and the shell. This corresponds to the actual operating conditions of the bridge structure pillars: in the upper part they are subjected to compression over the entire cross-sectional area from the crossbar, and at the bottom of the entire area they rest on the grillage. Additionally, when a load is simultaneously applied to both concrete and the shell, pipe-concrete structures operate more efficientl. This is how tests were performed in a number of studies [2, 8, 20, 24].

The samples were tested for short-term compressive loading. Prior to the start of the test, in order to ensure axial compression, the rack sample was centered on the base of the power plant. The load on the samples was applied in steps with a step of 50 kN. At each stage, the load was fixed for 30 seconds when time readings were taken from all the installed strain gauges. After that, the load increased to the next stage. The test was performed until the rack was destroyed. The samples installed prior to the testing are shown in Fig. 4.

a) b) c)

Fig. 4. Samples of concrete-filled hybrid poles 1 m long before compression test with fiberglass sheaths:
a) brand CA-20; b) CO-40 brand; c) brand KT-18

3. General description of the nature of the destruction of samples. During the test, the theore-tical assumption was confirmed that the tensile strength of the shell in the transverse direction mainly determines the load-bearing capacity of the hybrid rack with a composite shell. It was therefore the transverse fractures of fiberglass shells of three grades during compression of the samples of hybrid racks that prevented their further resistance to com-pressive loads (Fig. 5).

Samples of hybrid racks with shells of three grades were destroyed in the transverse direction in the place of the greatest transverse pressure of the core concrete on the shell, whereas in the longitudinal direction their overall integrity was preserved. If the compressive load is applied only to the concrete core (excluding the shell), the hybrid rack collapses earlier sustaining a much lower load.

a) b)

Fig. 5. Hybrid strut compression defects:
a) destruction of the shell from the transverse pressure of concrete;
b) destruction of the shell and concrete in the longitudinal direction did not take place

4. Numerical results of an experimental study. Graphs of the dependence of relative deformations of composite shells filled with concrete of three grades on the applied compressive load are given in Fig. 6.

Through the course of the experiment, transverse deformations developed quite rapidly, which indicates the pressure of the concrete core on the shell and compression of the core of the latter. The initial non-linear sections of the curves are caused by the effect of compression of concrete by shells. The relative deformations of the shells measured during the tests are equivalent to the deformations of the concrete core of the rack: the longitudinal shortened shells and the cores which are limited by the compressive unit of the power plant and the base below are identical. In the transverse direction, the deformations are also equal: a comprehensively compressed concrete core expands by an amount equal to the annular expansion of the shell; even following the destruction of the rack, the shell did not separate from the core (except the destruction zone).

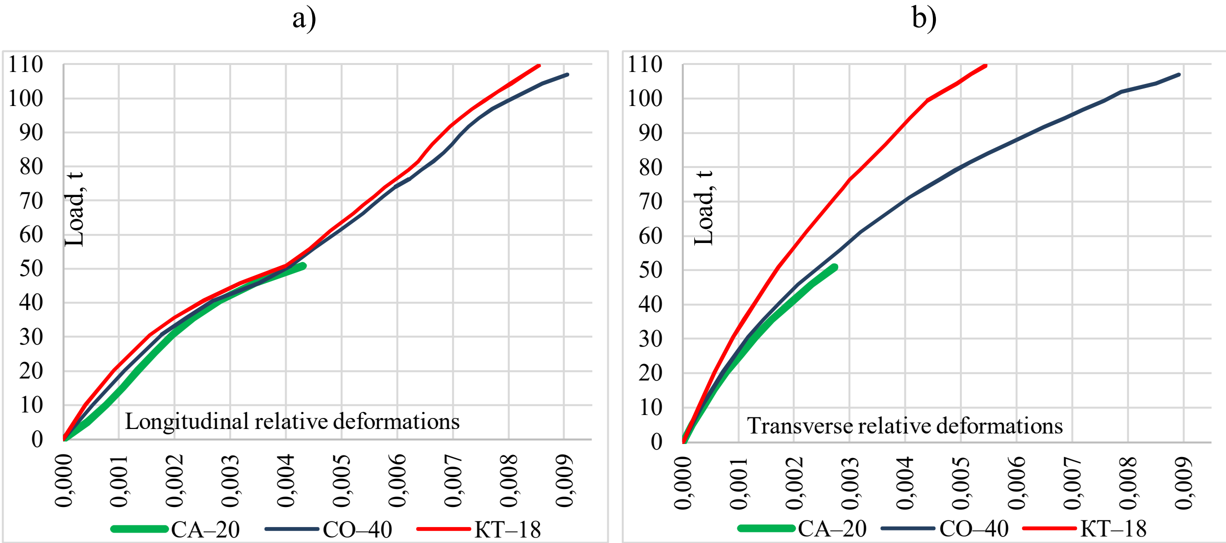

Fig. 6. Graphs of the increase in relative strains under compression
for samples of hybrid racks 1 m long with shells made of diverse grades of fiberglass:
a) longitudinal; b) transverse

As the shell is adjacent to the concrete of the hybrid rack, when the hybrid rack is compressed, its outer shell prevents the free lateral expansion of the concrete core. In this case, the concrete core of the hybrid rack transfers the internal stresses arising in it not only to the foundation, but also to the outer fiberglass shell. As a result, the concrete core operates under conditions of not uniaxial, but triaxial (all-round) compression resulting in a considerable increase in the load-bearing capacity of the hybrid rack (compared to the total strength of its individual elements).

The obtained values of relative deformations enable us to calculate the stresses of the shell and the concrete core of the hybrid rack. Fig. 7 shows the shell and core stresses that take place when an external compressive load N is applied to the rack: σ_{κ}^{x}, σ_{b}^{x} are internal longitudinal stresses of the fiberglass shell and concrete core; σ_{κ}^{r}, σ_{b}^{r} are internal transverse (radial) stresses of the fiberglass shell and concrete core (in our case $\sigma_{b}^{r} = -\sigma_{\kappa}^{r}$); σ_{κ}^{θ} are internal tangential (tangential) stresses of the fiberglass shell.

The values of the longitudinal stresses of the concrete core calculated theoretically from the author's dependences of the mathematical model of the hybrid rack were checked by means of comparing with the stresses that were calculated using the values of relative deformations measured during the experiments. Similarly, according to the results of the experiment, transverse (radial) stresses were checked. Comparison of the average values of stresses in concrete of hybrid props with shells of various grades is shown in the graphs of Fig. 8.

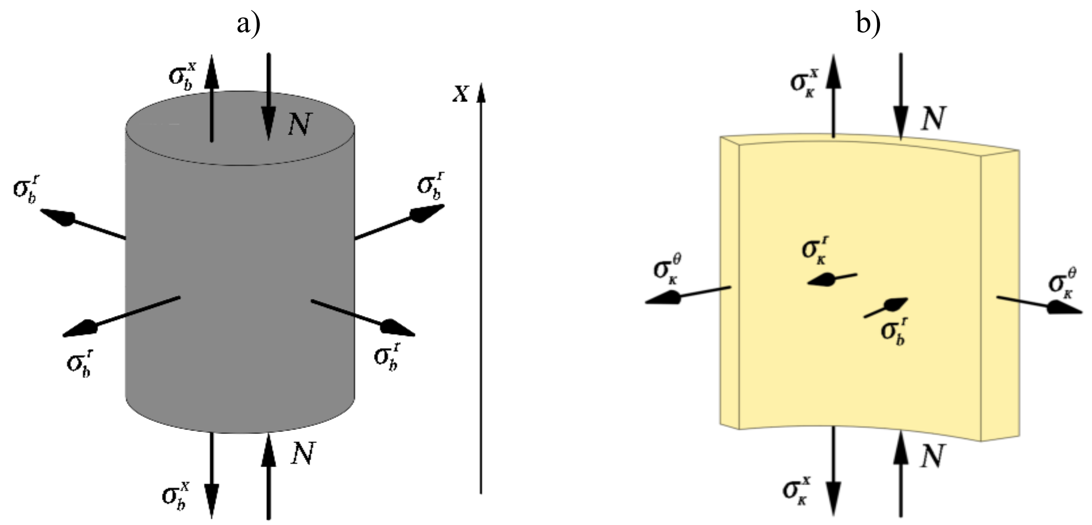

Fig. 7. Scheme for understanding the stress state of the elements of the hybrid rack: a) concrete core; b) fiberglass shell

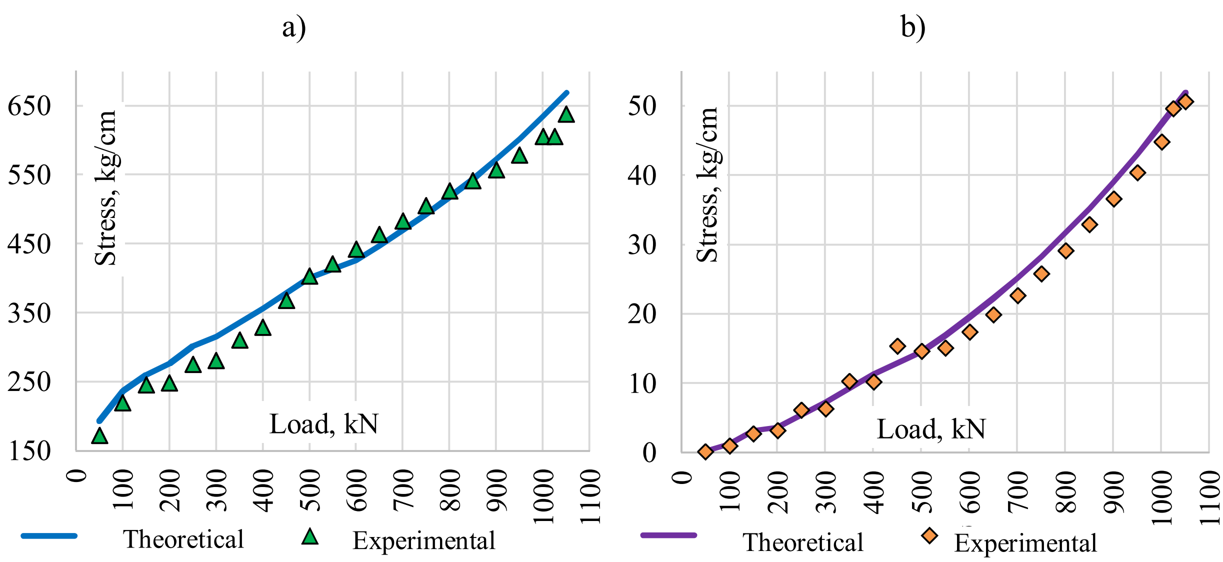

Fig. 8. Comparison of theoretical and experimental average stress values of the elements of hybrid racks for fiberglass shells of various grades filled with concrete: a) stresses of the concrete core in the longitudinal direction; b) transverse (radial) stresses

A comparison of the theoretical values of the stress strain of the elements of hybrid racks with the results of an experimental study showed their good convergence: the average discrepancy was 7 %. In an experimental study on the compression of samples of hybrid racks, the following were recorded:

1. A considerable increase in the strength of a comprehensively compressed concrete core in a composite shell. Previously, this phenomenon was repeatedly proven for steel-pipe concrete structures [1, 5, 7, 10, 16], whereas these tests confirmed an increase in the strength of

the concrete core in the case of using an outer shell with different physical and mechanical properties in the transverse and longitudinal directions. Such a hybrid structure can become an alternative to steel-pipe-concrete rack structures that have performed well in construction. The highest compression value perceived by a sample of a hybrid strut 1 m long was 111.07 tons. This is 2.07 times more than the total strength of concrete and this shell separately, and 3.18 times more than the strength of a concrete strut of the same section;

2. The identity of the mechanics of work and destruction of fiberglass shells of various manufacturers and types of production was fixed;

3. The loss of strength of specimens of reduced dimensions as shown by theoretical calculations using the Euler formula takes place prior to the loss of stability;

4. The shell did not separate from the concrete during the impact of a compressive load on the strut structure. Following the destruction of the shell from the transverse pressure of concrete, the hybrid rack loses the ability to perceive the load, however, the shell does not separate from the concrete except the destruction zone;

5. The lateral tensile strength of the shell largely determines the load-bearing capacity of the composite shell hybrid strut. Destruction of hybrid racks under compression took place precisely due to the destruction of fiberglass shells from the transverse pressure of concrete.

Conclusions

1. Experimental studies of hybrid struts have been performed which have shown the viability of using fiberglass structural elements in the strut supports of bridge structures which were not previously employed in such structures.

2. Comparison of the load-bearing capacity of a hybrid strut with a combination of design loads acting on the struts of bridge structures has shown that hybrid struts make it possible to perceive the impact of such values where the structures of existing bridge structures are operated.

3. Through the course of experimental studies, the possibility of using fiberglass shells as external structural elements of rack supports of bridge structures was confirmed.

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