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EXPERIMENTAL STUDY OF DEFLECTIONS AND BREAKING LOAD ON ICE REINFORCED WITH LONGITUDINAL ROD ELEMENTS FROM POLYPROPYLENE AND FIBERGLASS

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To date, the issue of using ice-based composite materials for engineering construction under harsh weather conditions remains poorly understood. Application of ice as a construction material is favored by its ease of use and low manufacturing cost. In turn, ice can be reinforced with various additional materials that change its physical and mechanical properties as part of an ice-based composite material. The results of an experimental study of the behavior of reinforced ice beams under pure bending are discussed. For reinforcement, longitudinal rods made of fiberglass and polypropylene with different physical and mechanical characteristics were used. The results of the study were compared with previous experiments on loading ice beams reinforced with steel armature. It is concluded that the proposed materials can be efficiently used to improve the mechanical characteristics of the ice. There is a positive effect of polypropylene on the deformability of the samples, as well as their bearing capacity. Schematic diagrams of deformation of ice beams when reinforced with steel and fiberglass armature and with polypropylene rods are presented. Prospects for the use of fiberglass and polypropylene rods in the ice-based composite materials are discussed.

Keywords: *ice beam, reinforcement, pure bending, carrying capacity, experimental research.*

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INTRODUCTION

In terms of the length of inland waterways, Russia ranks second in the world after China. In vast areas of the Far North, Siberia, and the Far East, where transport infrastructure is virtually absent, the main means of transportation and cargo delivery are river vessels. However, today, cargo transportation by inland waterways in Russia accounts for less than 1% of the total transport operations. Among the many reasons for the decrease in cargo turnover, the limited possibility of navigation in winter occupies an important place. In this regard, the issue of using the ice cover as ice crossings, winter roads, and cargo-carrying platforms is becoming increasingly relevant.

Examples of the successful use of ice for the engineering construction have been known since the beginning of the 20th century [*Nagrodsky, 1935; Lorch, 1977*]. With the intensive development of the Arctic basin, the task of designing and constructing ice aerodromes also arose, which required a deep understanding of the physical and mechanical properties and structure of the ice cover. In that time, K.F. Voitkovsky investigated the mechanical properties of ice [*Voitkovsky, 1960*]. J.T. Wilson, based on experimental data, developed a theoretical model of the behavior of the ice cover under the influence of single and paired load movements [*Wilson, 1955*]. The dependences of the stress-strain state of the ice on the speed of movement and other characteristics of various vehicles were experimentally studied [*Squire et al., 1988; Takizawa, 1988*]. Methods for calculating the ice cover rivers and reservoirs for the purpose of setting up temporary construction sites, access roads, and crossings were developed [*Bychkovsky, Guryanov, 2005*]. However, the increase in the mass of transported cargo and the complex behavior of the ice cover under static and dynamic loads necessitate the development of new approaches to the use of ice as a composite material of increased strength with specified physical and mechanical properties.

It was demonstrated that the ice strengthening at the microlevel can be achieved via adding fine particles (fibers, fine fibers, and some water-soluble compounds) to the ice cover [*Vasiliev et al., 2015; Cherepanin et al., 2018; Buznik et al., 2019*]. Fillers in the form of polymers of various chemical compositions and morphologies can be used as reinforcement elements [*Buznik et al., 2017*].

Traditional methods of increasing the bearing capacity of the ice cover consist of the additional freezing of ice from below or from above, strengthening the ice with wooden track flooring, etc. Experience in practical implementation of these methods shows that the physical and mechanical properties of ice strongly depend on external factors at the time of freezing and may not always correspond to the required operational characteristics. Geosynthetic materials can also be used as reinforcement [*Sirotyuk et al., 2016*]; the greatest effect is achieved when using fiberglass meshes [*Yakimenko, Sirotyuk, 2015*]. Earlier, the authors obtained the results of an experimental and numerical study of the stress-deformed state of ice samples enhanced with longitudinal and transverse reinforcing elements made of steel and various modern composite materials [*Kozin et al., 2019a*]. The efficiency of using different reinforcement schemes to increase the bearing capacity of ice was evaluated. The bearing capacity of the samples with a high degree of rigidity increased significantly (up to 400%). However, the use of steel reinforcement has a number of technological and environmental limitations, and the efficiency and duration of operation of the ice crossing also depends on the elastic-plastic properties of ice caused by the introduction of elements with elastic properties into it.

The aim of this work was an experimental study of destructive an deflecting loads on ice samples reinforced with different number of elastic elements located in the zones of tension and compression under load.

PREPARATION FOR THE EXPERIMENTAL STUDIES

Tests of ice samples are carried out by three methods: by destruction of ice beams lying freely on supports, by destruction of ice consoles, and by destruction of a round ice plate lying freely on an annular support loaded in the center [*Stepanyuk, 2001*].

Within the framework of this study, the optimum method turned out to be the destruction of ice beams lying freely on two supports. The scheme of the test bench is shown in Fig. 1 [*Kozin et al., 2019b*].

The study was carried out according to the recommendations of the Committee on Ice Research and Engineering of the International Association of Hydro-Environmental Engineering and Research (IAHR) [*Test methods..., 2021*].

The length of the ice beams was 2000 mm, width and height 200 mm. As a reinforcing material, longitudinally spaced rods made of fiberglass composite reinforcement (FCR) and polypropylene rods with tubular cross-section (PRTS) placed in a specially made hermetically sealed formwork, which was filled with water and exposed to negative temperatures were used. The number of elements located in the zones of stretching and compression to ensure spatial rigidity and the integrity of the frame was 2–3 pieces for the FCR beams and 1–3 pieces for the PPTS beams. The rods were located at the same distance from one another and the neutral axis. An example of the PRTS reinforcement scheme is presented in Fig. 2.

As the PRTS rods in the ice samples had a significant diameter of 32 mm, it was decided to conduct tests for the beams reinforced with only two elements. For each reinforcement scheme, three ice samples were prepared, which were frozen under natural con-

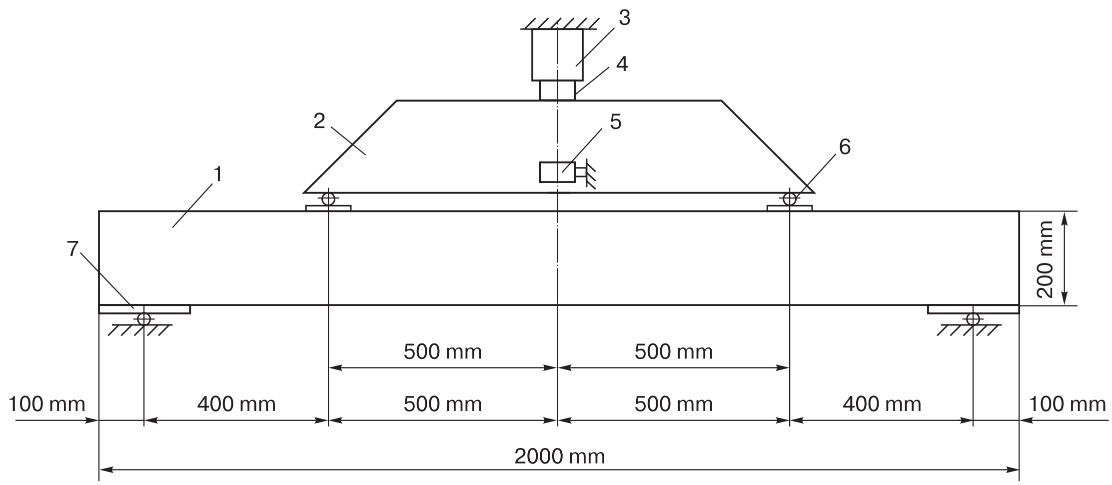

Fig. 1. Experimental installation scheme:

1 – ice beam; 2 – distribution beam; 3 – hydraulic cylinder; 4 – SH-20 weight terminal; 5 – LAS-Z vertical displacement sensor; 6 – hinge supports of the distribution beam; 7 – hinge supports of the ice beam [*Zemlyak et al., 2019*].

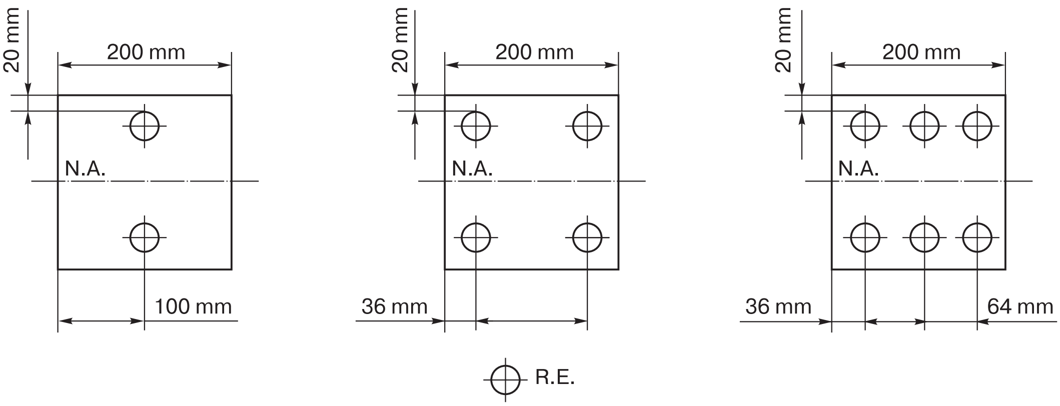

Fig. 2. Schemes of ice reinforcement with propylene rods of tubular section.

N.A. – neutral axis. R.E. – reinforcing element with the gravity center designation.

ditions at temperatures from –30 to –15°C for 7 days. The thickness of the protective layer of ice from the lateral plane of the beam to the nearest surface of the reinforcing element was 20 mm. Loading was carried out until the integrity of the sample was lost and pronounced through cracks appeared. The loading rate for all experiments was constant and equal to 135 kPa/s.

A GP2Y0E03 digital infrared vertical displacement sensor and an LPA-22t weight load cell with an SH-20 weighing terminal were used as measuring equipment. The destruction of samples was recorded by a high-speed high-resolution video camera VLXT-50M.I.

The experiments were carried out from December 2020 to February 2021 at ambient temperature from –20 to –15°C.

To assess the nature of the work of ice samples, the experimental data were compared with the results of loading of nonreinforced ice beams of similar size and beams reinforced with A400 metal armature with the same number of longitudinal connections (Fig. 3) [*Zemlyak et al., 2019*].

The mechanical characteristics of reinforcing materials are given in Table 1.

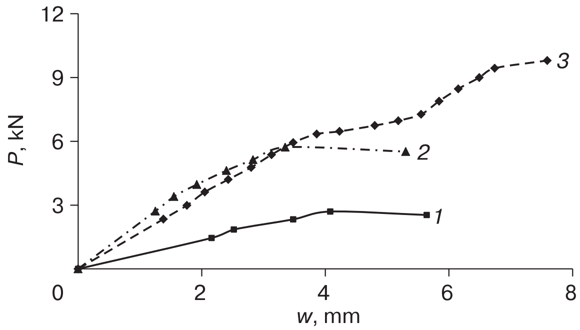

Fig. 3. Experimental load–deflection dependences for previously tested samples:

1 – nonreinforced sample; *2* – A400-4-6; *3* – A400-6-6.

Table 1. **Mechanical characteristics of reinforcing materials**

Parameter	A400	FCR	PRTS
Tensile strength limit σ_{bt}, MPa	365	168	50
Compressive strength limit σ_{bc}, MPa	365	63	50
Initial modulus of elasticity *E*, MPa	$20 \cdot 10^4$	$50 \cdot 10^3$	$1.5 \cdot 10^3$

MAIN RESULTS OF MODEL EXPERIMENTS

Figures 4 and 5 demonstrate a comparison of the averaged load–deflection dependencies obtained by processing the results of at least three experiments for nonreinforced ice samples and samples reinforced with FSR and PRTS with different amounts of reinforcing elements in the zones of tension and compression. In the names of FCR, PRTS, and A400, the first digit is the total number of rods in the section, the second digit is the diameter of the reinforcing element.

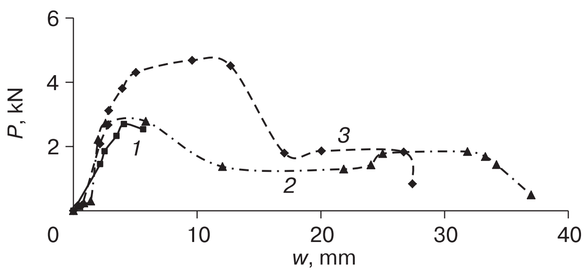

Fig. 4. Experimental load–deflection dependences for samples with fiberglass composite reinforcement:

1 – nonreinforced ice; *2* – FCR-4-10; *3* – FCR-6-10.

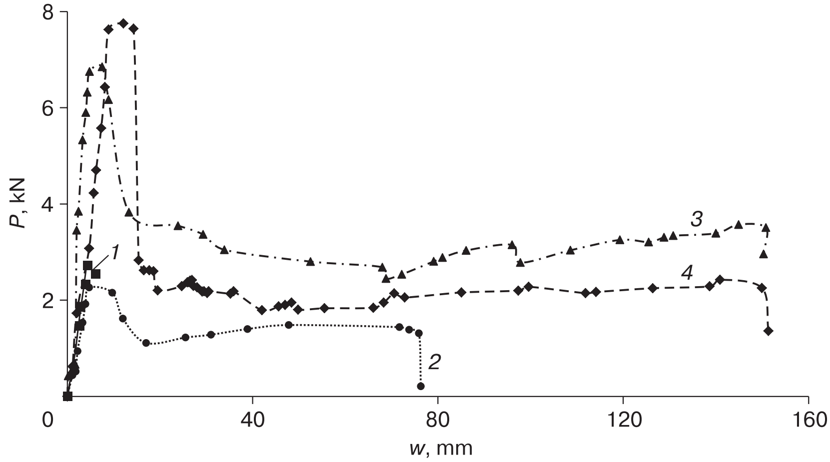

Fig. 5. Experimental load–deflection dependences for samples reinforced with polypropylene rods of tubular section (SPTS):

1 – non-reinforced ice; *2* – PRTS-2-32; *3* – PRTS-4-32; *4* – PRTS-6-32.

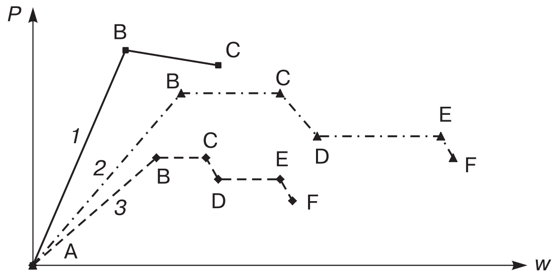

Fig. 6. Schematization of load–deflection diagrams for samples reinforced with various elements:

1 – A400; *2* – PRTS; *3* – FCR.

Figure 6 demonstrates the schematization of load–deflection diagrams when reinforcing samples with rod elements with different physical and mechanical properties.

Visualization of the destruction of an ice beam on the example of the PRTS-4-32 sample is shown in Fig. 7. The AB section is an elastic part of the diagram, where the relationship between stresses and deformations is linear and obeys Hooke's Law. The BC section is the deformability area, where the samples withstood the maximum destructive load $P_{\max}$ (Fig. 7*a*). In this section, the redistribution of forces between the material of the ice matrix and the rein-

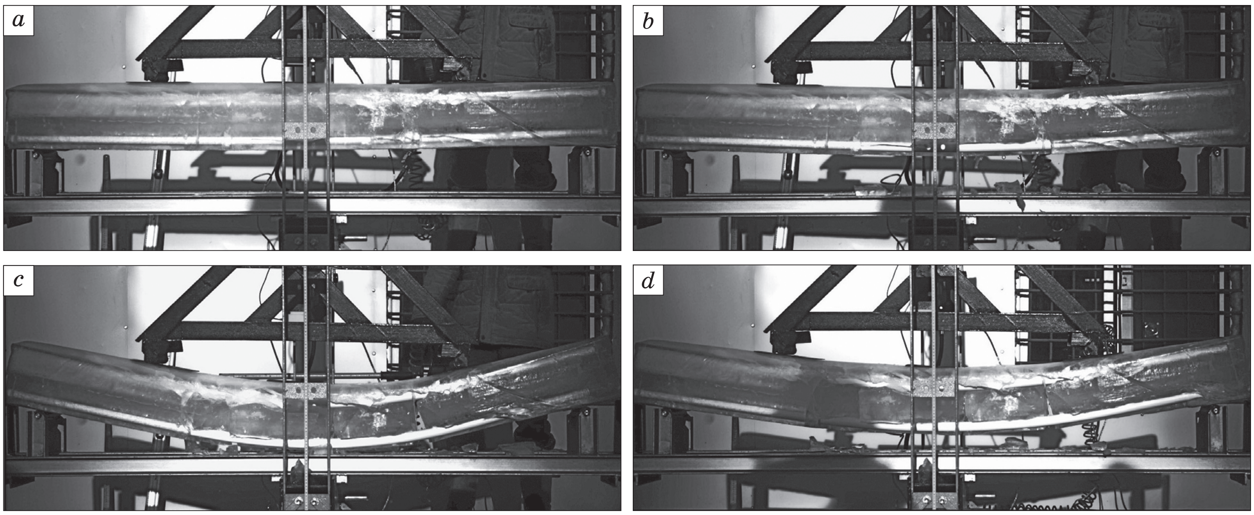

Fig. 7. Visualization of the process of destruction of the PRTS-4-32 sample according to the loading sections of the load–deflection diagram (see Fig. 6).

a – section BC; *b* – section CD; *c* – section DE; *d* – sample after removing the load.

forcing elements with the formation of the first cracks took place. It should be noted that for samples reinforced with A400 armature, the BC section displays the descending branch. For further analysis, we shall use the samples reinforced with PRTS and FCR. A decrease in the values of the load, the redistribution of the forces in the samples, and the most active formation of cracks was observed within the CD section; the destruction of ice took place in the tensile zone of the maximum bending moment (Fig. 7*b*). In the DE section, the main part of the load was taken by reinforcing elements, and plastic deformations accompanied by stress relaxation were observed in the ice, During loading, main through cracks were formed, but the reinforcing frames, despite significant deformations, continued to maintain the integrity of the ice beams (Fig. 7*c*). The greatest bearing capacity was shown by the samples PRTS-4-32 and PRTS-6-32, for which the maximum deflection value w_{max} was ~150 mm. Note that after removing the load, the samples partially returned to their original state, which indicates the efficiency of the elastic elements (Fig. 7*d*).

The main results of the model experiments are presented in Table 2.

Table 2. **Main results of model experiments**

Sample	w, mm	w_{max}, mm	P_{max}, kN
PRTS-2-32	5.06	75.9	2.24
PRTS-4-32	7.50	150	6.85
PRTS-6-32	12.1	150	7.75
FCR-4-10	2.60	27.90	2.72
FCR-6-10	5.54	36.93	4.31
No reinforcement	4.08	5.64	2.70
A400-4-6	3.35	5.30	5.72
A400-6-6	7.59	7.59	9.81

Note: In the names of FCR, PRTS, and A400, the first digit is the total number of rods in the cross section, the second digit is the diameter of the reinforcing element. w is the deflection when the maximum bearing capacity of ice samples is indicated; w_{max} is the maximum deflection of the sample after the complete or partial destruction of the ice matrix material and the redistribution of forces between the reinforcing material rods and ice; P_{max} is the maximum destructive load.

DISCUSSION

The tests demonstrated that the deformability of FCR-4-10 and FCR-6-10 samples was significantly higher than that of nonreinforced beams. Nonreinforced beams with comparable initial rigidity turned out to be significantly more brittle in comparison with beams reinforced with fiberglass armature, in particular FCR-6-10. For reinforced beams, after the P_{max} was reached, there was an insignificant area, where deformations continued to grow under a load of less than half of the maximum values (Fig. 4).

It can be seen in Fig. 5 that PRTS-2-32 samples did not have an obvious advantage in comparison with nonreinforced beams in initial rigidity and ultimate destructive load, but they showed significantly higher plasticity, even in comparison with the samples FCR-6-10. Samples PRTS-4-32 and PRTS-6-32 were subjected to significant bending during the experiments; they came into contact with the steel frame and rested against it upon a deflection of ~ 150 mm, which indicates the presence of a reserve of plasticity in such composite materials.

Comparison of the experimental results with the results of loading tests of the samples reinforced with A400 rods showed that the presence of steel reinforcement with a small diameter of cross section gives the structure the greatest rigidity; samples reinforced with A400-6-6 withstood the load P_{max} = 9.8 kN. However, the beams reinforced with steel armature were significantly inferior to FCR- and, especially, PRTS-reinforced ice beams in deformability and w_{max} value. It should also be noted that P_{max} for PRTS-4-32 and PRTS-6-32 were 6.85 and 7.75 kN, which greatly exceeded the P_{max} values for samples FCR-4-10 and FCR-6-10.

CONCLUSIONS

The model experiments have demonstrated good prospects of using surface reinforcement methods to increase the bearing capacity of the ice cover. When reinforcing elements exhibiting elastic properties are introduced into ice, the resulting load-deflection diagrams are more complex than when reinforcing ice with rigid elements in the form of metal armature.

The use of FCR and PRTS elements leads to a significant increase in the ultimate destructive load compared to nonreinforced samples. With the same number of rods, the use of PRTS ensures better indicators of deformability and ultimate destructive load in comparison with FCR.

At the initial stage of loading, PRTS samples are able to withstand a significant load, which drops sharply after the formation and opening of the main through cracks. Further ice hardening occurs in the compression zone, as a result of which the strength increases while maintaining the integrity provided by the reinforcing frame, and the load-bearing capacity of the beam also increases. Despite the large margin of deformability of the obtained composite materials, the diameter of the deflection bowl can be significant (which excludes the destruction of ice due to bending), and compression forces and reinforcing elements maintain the integrity of the ice providing an increased bearing capacity of the ice crossing.

The obtained experimental data on the strength of reinforced ice samples (reinforced ice beams) can be used in the future when conducting numerical experiments on loading a reinforced ice plate (ice crossing) with a moving load (vehicle). Numerical modeling will make it possible to replace the extremely complex and labor-consuming field tests and determine the optimum solutions for the reinforcement of long crossings and winter roads, the length of which can be hundreds of meters.

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