Experimental and numerical research of the stressed-deformed state of ice beams reinforced by surface reinforcement

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Abstract. It is known, that ice crossings are actively used in the Russian Federation, mainly in its eastern part, during the winter period. If the thickness of the ice cover is not sufficient for the safe exploitation of the crossing, it can be used the traditional methods of increasing the bearing capacity of ice. But traditional methods are not always effective, and the physical and mechanical properties of ice can strongly depend on various external factors. In this connection, the task of increasing the bearing capacity of ice by using alternative methods, for example, the introduction of reinforcing elements into the ice is becoming very relevant. The aim of the work was experimental and numerical study of stress-strain state of ice samples reinforced by surface reinforcing frame. The results of experiments on loading the samples were compared to the numerical results of calculations of ANSYS.

1. Introduction

In winter period in the case of absence of bridge structures or when the arrangement of ferry crossings is impossible the ice crossings arrange when the ice cover of required thickness is formed on the water barriers. If the thickness of the ice cover is not sufficient for the safe operation of the crossing, traditional methods of increasing of ice bearing capacity can be used, such as ice freezing from below, ice frosting from above, or ice strengthening with a wooden cover [1]. Practical experience reveals that the physical and mechanical properties of the ice cover, strengthened by these methods can strongly depend on various external factors (ambient temperature and presence of snow and wind when freezing). Ice, produced by the accelerated sprinkling method is often a firn mass capable of adhering to the wheels of vehicles and breaking away from the natural ice. This method is effective only for the ice cover of a certain thicknesses, and it increases the probability of formation of deep cracks in the ice. In this connection, the task of increasing the bearing capacity of ice by using alternative methods, for example, the introduction of reinforcing elements into the ice is becoming very relevant.

Yakimenko [2] describes experimental studies on the "surface reinforcement" of ice crossings by geosynthetic materials. Surface reinforcement by freezing the steel meshes was proposed by Nikitin [3]. A number of solutions are known in which steel elements are frozen to increase the bearing capacity in the ice cover [4, 5, 6, 7]. The method of surface reinforcement by introducing the welded steel frames into the relatively thin ice cover of 0.3-0.4 m thick can actually be sufficiently promising.
In paper [8], was present model experiments on testing the strength of ice reinforced with steel reinforcement, as well as numerical experiments on strengthening of ice samples by steel reinforcement and reinforcement of various types of composite materials. This paper presents a similar research, but other samples reinforcement schemes.

2. Preparations for the experimental and numerical research
To carry out the model experiments, a universal loading installation (Figure 1) was designed and assembled, this universal loading installation consisted of power frame, loading device and measuring module. The power frame consisted of pillars, frames, top and bottom beams. The loading device consisted of a hydraulic cylinder 3 with a nominal pressure of 9 atm. and distributing power beam 2. The force of the loading device was transmitted to the sample 1 through the hinge supports 6. The loading system was arranged so that it provided a pure flexure in the middle part of the span of the ice sample. The vertical displacement of the section of the sample in the middle of the span was measured by using non-contact laser sensor LAS-Z by Way Con (Germany) 5 fixed to an independent pillar. The load experienced by the sample was recorded by using an electronic weighing indicator SH-20 of TOKVES (Russian Federation) 4. The loading velocity for all samples was 135 kPa/s constantly.

A wooden framework made of boards of thickness 40 mm was arrange to manufacture the ice samples. The framework made it possible to prepare ice beams with dimensions L × B × H = 2000 × 200 × 200 mm. Two-layer polyethylene film with a thickness of 0.03 mm and a reinforcing frame were placed in the assembled framework. After that, the framework was filled with water. The liquid was exposed to low atmospheric temperatures (t < 0 °C) until its complete freezing. The time of preparation of the sample, depending on the weather conditions, was from 5 to 7 days at an ambient temperature of -16 °C to -28 °C.

An all-welded frame of steel reinforcement with a diameter of 6 mm was used to reinforce the ice beams. The frame scheme is shown in Figure 2.

Figure 1. Scheme for experimental installation: 1 - ice beam; 2 - distribution beam; 3 - hydraulic cylinder; 4 - weighing indicator SH-20; 5 - sensor of vertical displacements LAS-Z; 6 - hinged supports of a distribution beam; 7 - hinged supports of the ice beam.

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![Figure 2. The scheme of reinforcement of ice beam.](image)

Experiments on ice beams were carried out to evaluate the impact of the surface reinforcement of the stretched area strengthened with the reinforcing framework on carrying capacity of beams in the conditions of pure flexure.

The numerical calculation of stress-strain state of ice samples was carried out in the software system ANSYS Workbench, with using ANSYS Mechanical module. The model consists of 80160 finite elements and 89150 nodes. For ice, nonlinear finite element elements SOLID 65 in the form of a hexahedron were used to simulate elements that allow cracking in tension, and also allow calculations based on the [9].

The finite element BEAM188 was used to simulate the work of reinforcing materials. This is a beam element with flexural rigidity. Each longitudinal bar of the model was divided into 196 beam FE (Finite elements), each transverse bar into 18 beam.

The following mechanical characteristics of ice were used to calculate the reinforced ice beam: initial modulus of elasticity $E = 200$ MPa, uniaxial compression strength $R_b = 0.55$ MPa, uniaxial tensile strength $R_{bt} = 0.4$ MPa, density $\rho = 930$ kg/m$^3$, Poisson ratio $\mu = 0.3$.

The characteristics of the reinforcement: the initial modulus of elasticity $E = 2 \cdot 10^5$ MPa, the design resistance $R_s = 355$ MPa.

The mechanical characteristics of materials used to enhance ice in numerical experiments presented in table 1: hot-rolled reinforcement A400 (composite number 1); reinforcement fiberglass composite (composite number 2); reinforcement carbon (composite number 3); reinforcement aramid composite fiber (composite number 4); reinforcement combined with a combination of glass and basalt (composite number 5).
Table 1. Calculated mechanical characteristics of steel and composite reinforcement.

| Parameter name                      | № 1  | № 2  | № 3  | № 4  | № 5  |
|-------------------------------------|------|------|------|------|------|
| Maximum tensile stress, $\sigma_{bt,n}$, MPa | 365  | 168  | 840  | 448  | 320  |
| Compression resistance, $\sigma_{bn,n}$, MPa | 365  | 63   | 180  | 96   | 96   |
| Modulus of elasticity, $E$, MPa       | $10^4$ | $10^3$ | $10^3$ | $10^3$ | $10^3$ |

With account of the multiplication of the standard characteristics $\sigma_{bt}$ and $\sigma_{bn}$ by the corresponding coefficients, the calculated mechanical characteristics of used steel and composite reinforcement are shown in table 1.

3. The results of experimental and numerical research

A preliminary series of experiments on loading of unreinforced ice beams was carried out to evaluate the impact of surface reinforcement on the ultimate load-carrying capacity of samples. During the experiments, it was determined the beam deflection caused by the load applied to the test sample. According to the experimental data the destructive load was 3.6 kN, with a numerical calculation of about 3.9 kN [8].

![Figure 3](#)  
*Figure 3. Diagram of the dependence of the deflection of reinforced A400 samples from the load ( - results of experimental research, - results of numerical calculations performed in ANSYS Workbench 17.2.).*

Figure 3 presents the results of a model experiment with reinforced A400 sample. It is apparent that the maximum load that the samples sustained in the experiment was about 10 kN, which significantly exceeded the maximum load that the unreinforced sample could withstand. At this the formation of
through cracks in the tested samples occurred, and the maximum deflection reached 8.14 mm after which the complete destruction of the beams occurred.

As you can see, the results of model experiments and numerical calculations are in good agreement in the elastic zone. As a criterion for the destruction of the ice beam, a sharp increase in deformation was taken. The criterion characterized by a loss of bearing capacity and destruction of most of the section. In this case, the reinforcement did not reach the yield point, and as a result of the action of the bending moment in the middle of the beam span the destruction with the formation of extensive through cracks in the ice occurred.

Figure 4. Normal stresses in the median section of the ice beam of sample №2 upon failure.

An example of calculating the stress-strain state of a reinforced sample №2 with an fiberglass composite reinforcement in the ANSYS Workbench 17.2 software package is shown in Figure 4-8.

Figure 4 shows the displacement of the neutral axis of the modeled sample (bottom section tensions are within zero) when the breaking load of about 9.6 kN. Figure 4 shows that ice no longer works at the bottom of the section, but the load is received by the reinforcing material in the stretching zone.

Figure 5. Scheme of cracks in sample №1 (A400) during the experimental research

Figure 5 shows the appearance of cracks in the ice beam during the experiment.
Figure 6. Stresses in the reinforcement when breaking the sample №2 (MPa).

As can be seen from Figure 6 the stresses in the reinforcement of the stretched part did not reach the yield point and was about 143 MPa.

The main results of numerical calculations presented as diagrams of dependence of load from deflection for samples strengthened with reinforcement of various materials are shown in Figure 7.

Figure 7. Results of load-deflection calculations.

Taking into account the load at which the unreinforced sample destructed was 3.6 kN [8], it can be judged, that the bearing capacity of reinforced sample is much higher.

The stresses in the middle sections of each of the reinforced samples presented in Figure 8.

The reinforced sample №. 2 breacking before the remaining samples at a load of 9.6 kN. Analysis of the data shows that the use of reinforcing carcass of various composite materials significantly increases the bearing capacity of ice. The maximum carrying capacity in comparison with the unreinforced was demonstrated by a sample reinforced with steel reinforcement А400.

The lowest bearing capacity was demonstrated by samples strengthened with reinforcement material № 2, 4. The maximum stresses at a load of 9.6 kN (The load at which the weakest of the samples (No. 2) lost its bearing capacity) for samples reinforced with material № 1, 2, 3, 4, 5, were -0.168 MPa; -1.094 MPa; -0.664 MPa; -0.778 MPa; -0.68 MPa respectively. The fastest growth of normal stresses with increasing the load was observed in samples of composite №2, the slowest growth observed in samples reinforced with №1.
Figure 8. Distribution of normal stresses $\sigma_z$ in the beam section at load of 9.6 kN.

4. Conclusion

Resulting from the study, the following conclusions can be drawn:

As a result of experimental and numerical research, it was established that the use of surface reinforcement of ice with various materials under this reinforcement scheme it possible to increase the bearing capacity from 166 to 233%.

Destruction of samples in all cases occurred as a result of formation of extensive through cracks in the ice caused by the action of bending moment in the middle of the beam span. At this the reinforcement did not reach the yield point. In numerical calculations at the stages of failure the normal stresses in the lower part of the section approached zero.

The results of model experiments and numerical calculations are in good agreement in the elastic zone. As for deflections and destructive loads, deviations in the comparison of data did not exceed 8.9% and 33% respectively.

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