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BEARING CAPACITY OF REINFORCED ICE BEAMS EXPOSED TO SIMPLE BENDING

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The bearing capacity of reinforced ice beams exposed to simple bending under successively increasing loading has been studied in a series of laboratory experiments and by numerical modeling. The physical experiments are performed using a specially designed installation, with A400 steel reinforcement, 6 mm in diameter. The simulation is run in the *ANSYS* software for reinforcement with different composite materials in order to assess their efficiency qualitatively and quantitatively. The physical and numerical modeling results agree to a satisfactory accuracy.

Ice crossing, surface reinforcement, composite material, ice beam, physical experiment, numerical experiment

INTRODUCTION

Progress in hydraulic and transportation engineering for development of the Arctic, Siberian, and Russian Far East regions requires increasing amounts of works run in winter time on the ice of rivers and lakes [*Bychkovsky and Guriyanov, 2005*]. Ice is broadly used for crossing and transportation of cargoes in areas of harsh climate conditions and poor infrastructure. The bearing capacity and behavior of ice subjected to loading has been studied since recently using the models and principles of deformable solid mechanics to meet the challenge of increasing transported weights.

The existing regulations suggest a few basic ways to enhance the ice bearing capacity: boarding or ice thickening from above (by successive layered freezing of water) or from below (by inclined thermosyphons) [*Common House Needs, 1998*]. However, the conventional methods are poorly reliable and sensitive to external effects, such as presence of snow and ice during layered freezing, air temperature, etc. In this respect, improved ice reinforcement with various materials acquires special importance.

The reinforcement issues were discussed in a number of previous publications, including an inventory and classification of the available techniques and recommendations for the most efficient and commercially viable ways to increase the bearing capacity of ice crossings [*Yakimenko and Sirotyuk, 2014, 2015*]; experiments on geosynthetic reinforcement of ice from above [*Sirotyuk et al., 2016*]; geonet reinforcement with a new method [*Nikitin and Nikitina, 2015*]; mechanical properties of composite materials frozen into ice (with various modifiers, such as fir needles, carbon nanotubes, flax and glass fiber, wood chips, etc.) [*Buznik et al., 2017; Cherepanin et al., 2018*]. Yet, these methods can ensure no more than 75 % better bending strength of ice. Some other solutions imply steel reinforcement [*Kostenko et al., 2005; Kozin et al., 2016*] or surface reinforcement with 3D frames embedded in relatively thin ice of 0.3–0.4 m [*Kozin et al., 2018a*]. In the latter case, the use of continuously welded frames provides up to 86 % gain in the ice bending strength with lateral ties; the gain reaches 230 % with additional longitudinal ties in the framework top and base [*Kozin et al., 2018a,b*]. The presence of additional longitudinal ties in the lateral surface of the reinforcement framework is known to confine cracking along the sample height.

The bearing capacity of reinforced ice beams exposed to simple bending under successively increasing loads has been studied in a series of laboratory (physical) and numerical experiments. The reinforcement was made as a continuously welded ribbed steel framework with longitudinal ties in lateral planes. The performance of the suggested numerical model has been checked by varying the types of composite materials: glass reinforced plastic, carbon, aramid-based composite, and combined glass + basalt.

EXPERIMENTAL STUDIES

The strength and elastic properties of ice can be tested by different methods, according to (i) bending of beams lying freely on two supports; (ii) failure of floating consoles; (iii) failure of a circular ice plate lying freely on a ring support loaded at the center, etc.

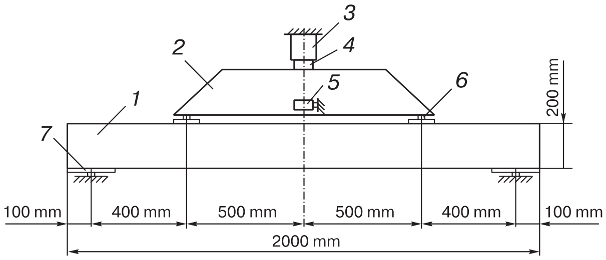

Fig. 1. Experimental layout.

1 – ice beam; *2* – spreader beam; *3* – hydraulic cylinder; *4* – stress gauge LPA-22t with a SH-20 weighing terminal; *5* – strain gauge LAS-Z; *6* – hinged bearing of spreader beam; *7* – hinged bearing of ice beam.

Fig. 3. Cracks appearing in ice beam.

[*Voitkovsky, 1960*]. In 1980, the ice research group of the International Association of Hydraulic Engineering and Research (IAHR) suggested a number of recommendations on the procedures for testing ice with regard to its features, using some optimal size ratios of the tested samples. Many publications show that the best results which allow reducing the effect of scale (size of samples) on the ice strength can be obtained with the ratios of equal beam width (B) and height (H) and a length of (8–8.5)H [*Kostenko et al., 2005*], or $L = 10H$ as in [*Maattanen, 1976*], or $B = (1–2)H$ and $L = (7–10)H$ as recommended by IAHR.

In this study, bending of free beams on two supports turned out to be the most suitable approach to the estimation of ice elastic properties. The loading experiments were run on a specially designed universal installation (Fig. 1) consisting of a carrier frame (vertical and horizontal support bars, a console, and upper and lower beams), a loading unit, and a measuring unit. The loading unit included a hydraulic cylinder (*3*) with a nominal pressure of 9 bars and a spreader beam (*2*) that distributed the load which was transferred to samples via hinges (*6*) upon 200 × 200 mm gaskets (the size of the ice beam cross section). The loading system was made such that it could provide simple bending in the middle of the ice span. The related vertical displacement of the sample at that point was measured on a *Way Con LAS-Z* contactless laser sensor (Germany) fixed on an independent bar (*5*), to an accuracy of 0.01 mm. The load was determined with an *TOKVES 4 LPA-22t* electronic stress gauge with an *SH-20* weighing terminal (Russia). The strength was determined in samples subjected to brief loading at a constant rate of 135 kPa/s. The sample failed 5 s after the onset of loading.

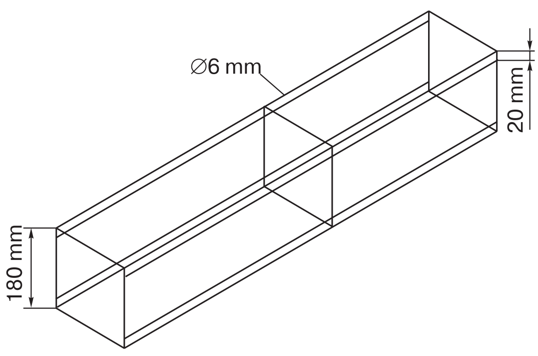

Fig. 2. Reinforcement of ice beam.

Ice samples of $L \times B \times H$=2000 × 200 × 200 mm were fabricated using a wooden frame of 40 mm thick boards. A 0.03 mm two-layer polyethylene film was placed into the assembled frame and the reinforcement was fixed below the ice beam surface in a plane-parallel orientation. Then the wooden frame was filled with water and exposed to negative temperatures till complete freezing. Fresh ice samples froze for five to seven days depending on air temperature, from –15 to –28 °C. The experiments were run in three series, with five samples in each, prepared in the same way. The samples were loaded along the direction of water crystallization. The data of the five runs were averaged; the difference between the results did not exceed 15 %.

The ice beams were reinforced with a continuously welded ribbed steel framework (A400) 6 mm in diameter (Fig. 2). Experiments on failure of the ice beams were performed to estimate the effect of surface reinforcement in extended and compressed zones on the bearing capacity of ice subjected to simple bending (Fig. 3).

NUMERICAL EXPERIMENTS

The model consisted of 80,160 finite elements and 89,150 nodes. The *SOLID 65* finite element for ice corresponded to the model of *Willam and Warnke* [*1974*] applicable to brittle inhomogeneous materials. According to the model, fracture occurs on the surface normal to the principal stress as the latter exceeds the specified yield strength.

Table 1. **Calculated mechanic properties of steel and composite reinforcement materials**

Parameter	Sample				
	1	2	3	4	5
Tensile strength limit $\sigma_{bt,n}$, MPa	365	168	840	448	320
Compression strength limit $\sigma_{bc,n}$, MPa	365	63	180	96	96
Young modulus E, MPa	$200 \cdot 10^3$	$50 \cdot 10^3$	$130 \cdot 10^3$	$70 \cdot 10^3$	$100 \cdot 10^3$

The behavior of reinforcing materials was modeled using the *BEAM188* element: a beam with specified bending stiffness, Young's modulus, shear modulus, Poisson's ratio, and yield strength. The longitudinal and transverse bars of the frame were divided into 200 and 18 finite elements, respectively. The relationship between the ice and reinforcement finite elements was assumed to be ideal. The reinforced ice beam design was based on the mechanic properties of ice: initial Young's modulus E = 300 MPa, uniaxial compression strength R_{bc} = 0.6 MPa, uniaxial tension strength R_{bt} = 0.5 MPa, density ρ = 930 kg/m^3, and Poisson's ratio μ = 0.3. The reinforcement parameters were: initial Young's modulus $2 \cdot 10^5$ MPa and a design strength of R_s = 355 MPa.

The mechanic properties of the reinforcement materials used for increasing ice bearing capacity in numerical experiments are summarized in Table 1: hot rolled steel A400 (sample 1); fiber glass composite (sample 2); carbon (sample 3); aramid fiber composite (sample 4); combined glass+basalt (sample 5).

RESULTS

The mechanic properties and estimates of the effect of surface reinforcement on the ultimate bearing capacity of samples were investigated in a series of preliminary loading experiments with non-reinforced ice beams by evaluating the loading-dependent bending of the beam. The critical loading was 3.6 kN in physical experiments and ~3.9 kN in simulation [*Kozin et al., 2018a*].

The laboratory testing results (Fig. 4) compared with the numerical calculations show that the maximum critical load for the reinforced samples (10.6 kN) exceeded notably that for non-reinforced beams [*Kozin et al., 2018b*]. The loading produced through cracks in the samples, and they failed upon a maximum displacement of 8.25 mm.

The results of physical and numerical modeling agree well in the elastic domain. The ice beam failure was identified using a criterion of dramatic strain increase and the ensuing bearing capacity loss and fracture over the greatest part of the cross section. The reinforcement did not reach the yield strength while the bending moment in the middle of the span produced through large cracks in the ice.

Stress and strain in the A400 reinforced ice sample were calculated in *ANSYS Workbench 17.2* (Fig. 4). The cracks were estimated using the strain criterion of Bazant [*Bazant and Cedolin, 1980*] for the range of –0.000 59 to 0.097 (Fig. 5). Positive values correspond to the nucleation and opening of cracks in the

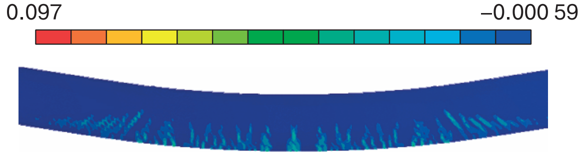

Fig. 5. Failure of sample 2.

Scale shows dimensionless strain according to cracking criterion.

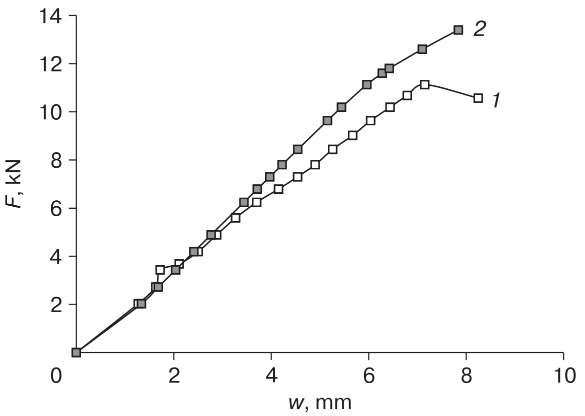

Fig. 4. Displacement (w) of reinforced sample (A400) as a function of load (F).

1 – physical experiment; *2* – numerical experiment (simulation in *ANSYS Workbench 17.2*).

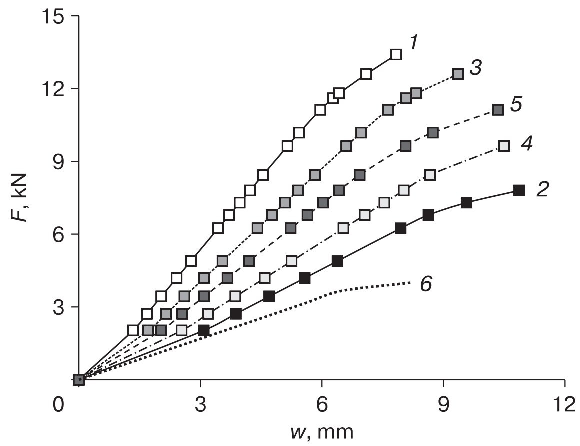

Fig. 6. Calculated displacement (w) of reinforced samples 1–5 (curves *1–5*) and non-reinforced sample (curve *6*) as a function of load (F).

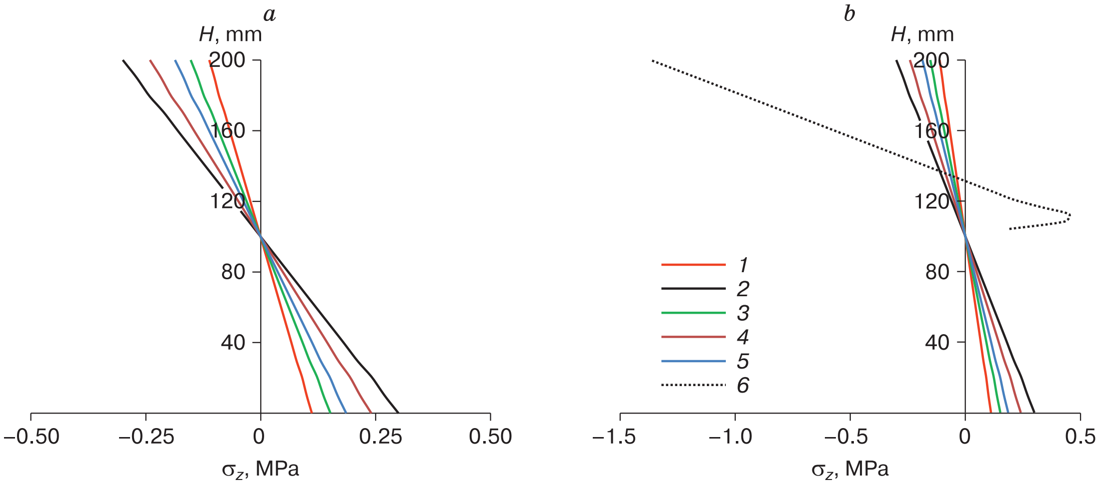

Fig. 7. Distribution of normal stress σ_z in ice along the beam height for reinforced samples 1–5 (curves *1–5*), at load E = 3.6 kN.

a: without non-reinforced sample; *b*: stress ratios relative to non-reinforced sample (curve *6*).

stretched zone of the beam expressed as stiffness loss in the finite elements of the discrete model. However, the reinforcement stress in the stretched zone did not reach the yield strength and were 81.5 MPa the highest.

The results of calculations are plotted in Fig. 6 as load vs. displacement for ice beams reinforced with different materials. The use of different reinforcement composite materials increased markedly the bearing capacity of the ice. It was the highest in sample 1 reinforced with A400 steel and the lowest in samples 2 and 4. The combined glass + basalt reinforcement (sample 5) provided the highest plasticity.

The stress pattern in the middle sections of each sample under a load of 3.6 kN is plotted in Fig. 7. A sharp stress change in the upper section of the non-reinforced sample (Fig. 7, *b*) and its absence in the lower part indicate that the sample lost its bearing capacity.

The highest stress values for reinforced samples 1, 2, 3, 4, and 5 were −0.11, −0.30, −0.15, −0.24, and −0.18 MPa, respectively, at the 3.6 kN load. Normal stress increase was the fastest in sample 2 with glass reinforced plastic and the slowest in sample 1 with the steel A400 reinforcement which showed the highest bearing capacity (Fig. 6).

CONCLUSIONS

1. The results of physical and numerical experiments agree well in the elastic zone. The misfit for samples reinforced with A400 steel is no higher than 5 % for maximum bending and 26 % for ultimate load.

2. The efficiency of different reinforcement materials embedded into ice in order to increase its bearing capacity has been estimated qualitatively and quantitatively. The use of 3D reinforcement made of various materials according to the specified design provides 116 % to 272 % improvement of the bearing capacity with glass reinforced plastic and steel A400, respectively.

3. In all cases, ice fails by developing large through cracks under the bending moment in the middle of the beam span. The failure occurs while the reinforcement is above the yield strength.

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