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FIELD INVESTIGATIONS OF FIRST YEAR ICE MECHANICAL PROPERTIES IN NORTH-WEST BARENTS SEA

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ABSTRACT

The paper contains description and results of investigations of first year ice mechanical properties that were performed during last four years in fiords of Svalbard, as well as in Barents Sea areas close to the archipelago. During the fieldwork, measurements of the ice temperature and salinity profiles through the ice thickness were carried out, and the ice flexural strength was determined through the cantilever beams bending.

New equations for calculation of the sea ice flexural strength have been constructed using the measured profiles of temperature and salinity through the ice thickness, and the derived formulas were compared with ones proposed by other authors or applicable for other freezing seas. As the results have shown, flexural strength of ice in fiords of Svalbard is close to the corresponding values of the Barents Sea ice, but all the considered equations for various regions differ from each other. Mostly this is because not only the ice temperature and salinity effect on flexural strength, but also the ice inner structure and deforming that, in turn, depend on weather conditions and ice regime in specified region. Flexural strength values determined cantilever beam tests are less than those obtained according to Timco&O'Brien equation for low ice salinity.

The results of numerical simulation of the floating cantilever beam bending using FEM were applied to analysis tensile stress distribution in the most loaded root section of the beam.

INTRODUCTION

Flexural strength is one of the crucial parameters used in ice-technology for assessment of ice loads of ice breakers and the level of ice loads on offshore structures. One of the methods to determine the ice flexural strength is loading of cantilever beams described in Schwarz et al. (1981).

This method includes several assumptions with major being as follows:

- cantilever beam is homogeneous and has similar lateral cross-section (rectangular) lengthwise;
- fragile breaking in the root section due to loading of the free end by vertically applied force; and
- low impact of water pressure on applied load.

This method for determination of the ice flexural strength has a number of advantages:

- Fairly simple physical interpretation of the strength indicator which is in reality the ice tensile strength.
- The test result is an integral characteristic of the ice flexural strength related to the whole ice thickness. The range of values based on a number of experiments is significantly lower than during bending tests of small ice samples made of separate ice layers.
- Similar ice breaking process by bending is observed when icebreakers and offshore structures interact with ice and when ice is broken by surface waves penetrating under the ice. The ice flexural strength values are used in theoretical models for practical calculation of ice loads on the structures.
- This method for determination of ice flexural strength is used during physical scale simulation in the ice model basin (Schwarz et, 1981) which enables direct comparison of flexural strength values in field and model conditions.

A significant fault of bending tests for cantilever beams is the difficulty of their implementation in field conditions. A number of researchers noted perceptible correlation between ice flexural strength and ice salinity. Timco and O`Brien (1994) reviewed quite many statistical materials to obtain a formula for calculation of the sea ice flexural strength based on a known brine volume which in turn is determined by measured temperature and salinity of the ice. This approach can significantly simplify the procedure for determination of ice flexural strength as a difficult cantilever beam making process can be replaced with measurements of the ice temperature and salinity profile. Particularly, flexural strength of ice in fiords of Svalbard may be assessed using the ice salinity and temperature data given in Høyland (2009). However Timco and O`Brien (1994) equation is based on the results of a large number of field tests series in different regions (over 1500 tests). There is a significant variance between experimental points which prevents from assessing the ice flexural strength for a specific region with a given degree of accuracy.

In 2009-2012 a number of ice cantilever beam tests was conducted in the fiords of Svalbard. Additionally to determination of the flexural strength, the purpose of the surveys was to build the correlation between the flexural strength value and ice salinity/temperature, and compare resulting equation against Timco and O`Brien (1994) recommended for use in ISO 19906 (2011), as well as against the other data.

PECULIARITIES OF ICE COVER FORMATION IN FIORDS OF SVALBARD

The main feature of Svalbard archipelago is its location at the boundary of spreading warm waters of the North-Atlantic current and ice cover of the Arctic basin with the zone of sustainable western transfer of air masses along the Icelandic Kara depression. The western coast of Svalbard is washed over by Spitsbergen Current with average water temperature of 1.9^{o}C and salinity of 35 ppt. The impact of the current is absence of ice in the open part of the western archipelago coast, including absence of ice in outer fiord areas protruding onshore. The warm current does not impact deep areas of fiords and therefore inner zones of extended bays in winter are covered by thermal ice (Fig. 1). Very frequently a similar situation is aggravated by islets in the outer parts of the fjords which prevent ingress of warm waters. At the top of many fiords, there are glaciers flowing off Spitsbergen mountains. Discharge of melt fresh water from the glaciers results in the formation of a warm sea water zone at the entrance to the fiord. This water flows with the current and often forms an ice-hole, while at the fiord top there is fresh water runoff from the glacier.

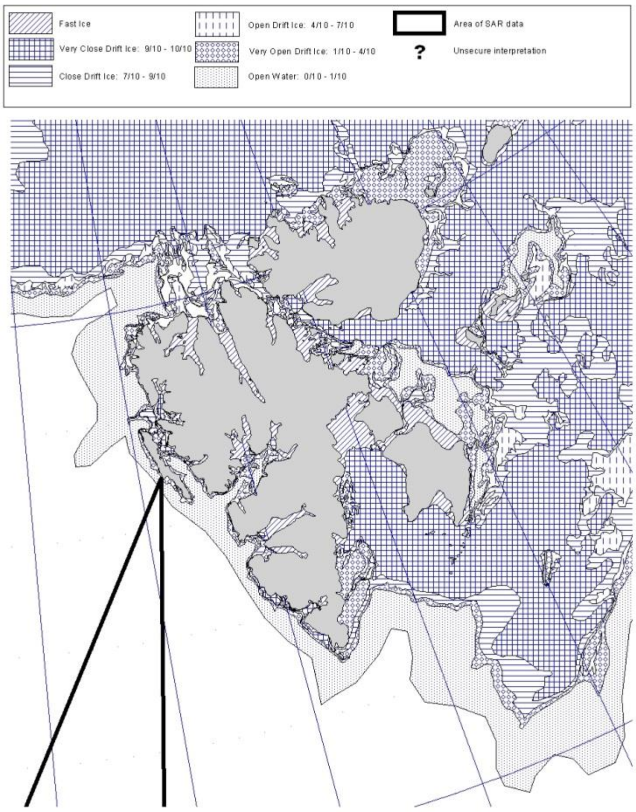


Figure 1. Ice cover near Svalbard archipelago

In winter the ice cover mainly forms near glaciers and on shallow water near shores and then spreads to more seaward areas of the fiords. Therefore, ice thickness on the same fiord increases as it gets closer to the glaciers (Fig. 2). Ice thickness changes within the same fiord as well as from fiord to fiord. This feature allows experimenting with sea ice properties at the sites located comparatively close to each other and that significantly simplifies the field process and equipment delivery.

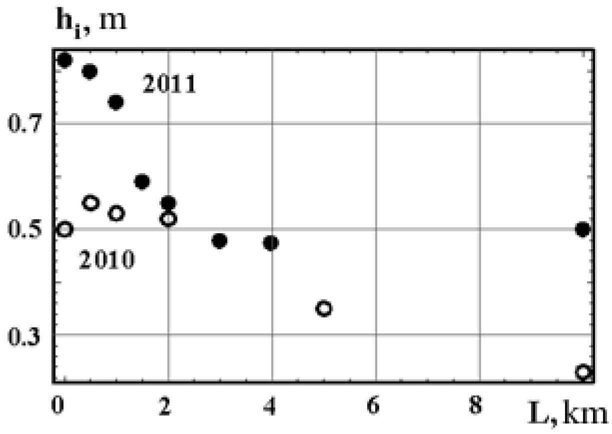


Figure 2. Ice thickness change along Temple fjord from Tuna glacier

Vertical distribution of ice temperature along the ice thickness shows linear correlation from February through April and becomes more homogeneous in May and June. At that time it becomes possible to survey fairly warm sea ice with thickness reaching 1m and surface ice temperature exceeding water freezing temperature at the lower ice boundary.

DESCRIPTION OF THE POLYGONS FOR BENDING TESTS

Given all possibilities available, three points were selected as bending test polygons, including point 1– Svea settlement in Vanmien Fjord, point 2 – Temple Fjord, and point 3 – Advent Fjord near Longyearbyen (Fig. 3).

The site in Svea Vanmien Fjord is situated deep into the fiord. The entrance to the fiord is blocked by narrow long Axeloja Island with narrow passes into the fiord from both sides of the island and preventing warm current from entering the bay. The fiord is covered by a stable ice cover lengthwise from December through June. The sea depth at the site is several meters.

Temple Fjord is an inner fiord of larger Is-Fjord heavily impacted by Spitsbergen Current as compared to Van Mien Fjord. The outer part of Temple-Fjord is impacted by Atlantic waters penetrating into Is-Fjord. Therefore in relatively warm winters there is an open water glade at the entrance to the fiord. There are two glaciers (Tuna and Van Post) at the top of the fiord, which support melt water runoff at the top of the fjord. The fiord stretches about 23km where ice cover variance can be demonstrated due to changing hydrology at the entrance and top of the fiord. Ice thickness at the fiord is distributed as is shown in Fig 2.

The third polygon is situated directly within Longyearbyen on Advent-Fjord which is a short bay with a wide open entrance facing the big fiord (Is-Fjord). As Advent-Fjord is open, fiord ice is heavily impacted by wind and waves. Therefore, a sustainably permanent level ice in the fiord cannot be observed: waves destroy resulting land-fast ice, east winds carry away destroyed ice to the open part of Is-Fjord; when wind changes westwards the fiord is swarmed with broken ice from adjacent basins. Only when there are not moderate winds, ice in Advent-Fjord is preserved in Longyearbyen zone. Tests in Advent-Fjord were conducted on young level thermal ice formed in open water after icebreaker manoeuvres.

Figure 3. Polygons for conducting cantilever beam tests:
1 polygon – in Svea Vanmien-Fjord, 2 polygon – in Temple-Fjord, 3 polygon – in Advent-Fjord near Longyearbyen

DESCRIPTION OF THE BENDING TEST PROCEDURE

The ice flexural strength was determined by loading of cantilever beams in-situ according to the traditional procedure (ITTC). The beams length was about 5.0-8.5 ice thickness. It was found in the previous numerical investigations of the beam tests based on FEM (Frederking and Svec, 1985; Svec et al., 1985) that elementary beam bending theory is suitable, if a) test beams should have a width-to-thickness ratio of about one, b) the root should definitely be terminated in a stress relief hole. In the presented tests the beams width was 1.0-2.5 ice thickness, and in most cases the ratio was about one. All the beams roots were terminated by vertical stress relief holes of about 100mm diameter.

The following equipment was fabricated and installed for the tests (Fig. 4):

- Steel loading rig transferring force from immovable ice cover to the loaded ice beam;
- Hydrosystem (Single-Acting Cylinder RC-154, Electric Pump ZE-Series)
- Generator (3-phase, 400 V)
- Load cell NTT C8S- 82-1-100kN
- Data Logger Campbell Scientific CR1000

Figure 4. Equipment for performing cantilever beam tests

After preparation of the cantilever beam, it was loaded by hydrocylinder until breakage with simultaneous recording at 100Hz of the loading force (Fig. 5). Once the beam was broken, it was measured.

The impact of the snow cover on flexural strength was not studied. In order to keep static balance, snow was kept on the cantilever beam. The snow was removed in the beam root to observe cracking.

In level ice nearby the beam root a cylindrical ice core was drilled to measure the temperature and salinity profiles (Fig. 6).

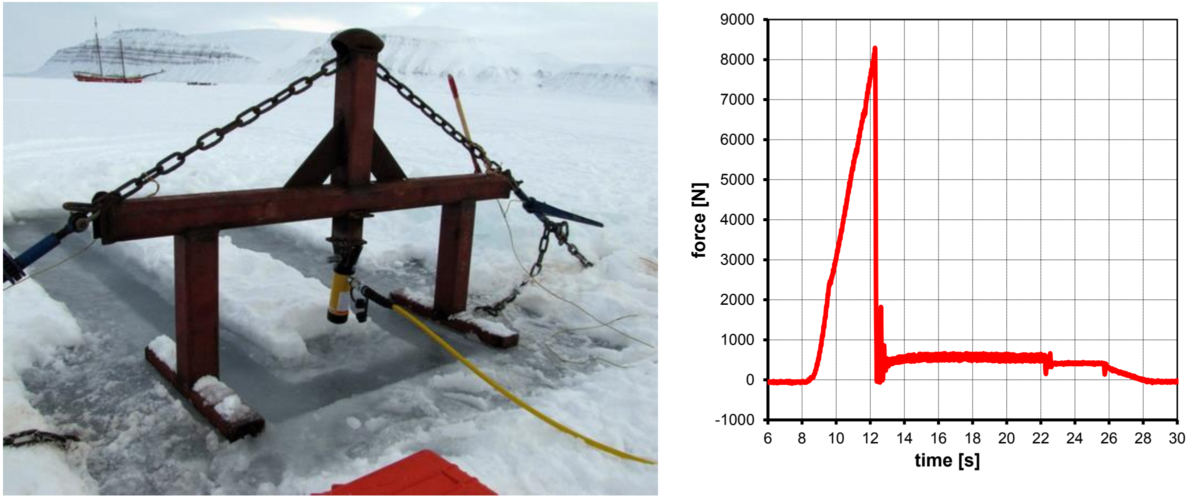


Figure 5. Experimental set-up before the bending tests (left) and an example of the force record (right)

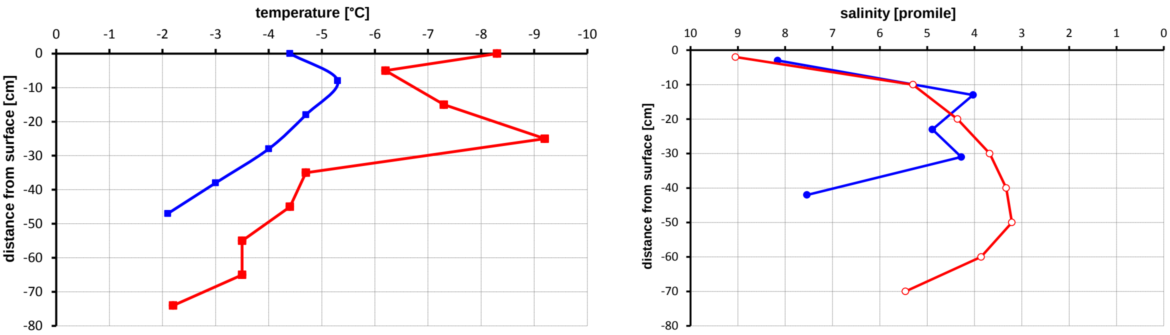


Figure 6. Typical temperature and salinity profiles through the ice thickness in Svalbard fiords

ANALYSIS OF THE FIELD WORK RESULTS

Table 1 contains geometry of the beams, average salinity and temperature through the ice thickness. The last column contains the ice flexural strength calculated from simple elastic beam theory using the following equation: $\sigma_f = (6PL)/(bh^2)$ where P is breaking force, L, b, h are the beam length, width and ice thickness correspondingly. As it was indicated by Svec and Frederking (1981), this approach is based on several assumptions that are applied to the presented case. Main of the assumptions is: shear stresses are neglected, ice is a homogeneous, isotropic material, and the ice beam under test behaves as a cantilever elastic beam.

Analysis of the results is based on the correlation of ice flexural strength σ_f and square root of ice brine volume ($\sqrt{\nu_b}$) calculated using Frankenstein and Garner (1967) equation:

$$\nu_b = S\left(\frac{48.185}{|T|} + 0.532\right), -22.9^\circ\mathrm{C} < T < -0.5^\circ\mathrm{C} \qquad (1)$$

where S and T are average values of ice salinity and temperature through the ice thickness, respectively.

Fig. 7 shows that resulting experimental points can be approximated within the surveyed ice salinity and temperature range as the following equation:

$$\sigma_f = 0.5321\exp(-3.339\sqrt{\nu_b}). \qquad (2)$$

Table 1. Results of the field works

Place	Date	Length [m]	Width [m]	Thickness [m]	Salinity [ppt]	Temperature [° C]	Flexural strength [kPa]
Tempel-fjorden	05.03.2010	1.97	0.64	0.23	5.57	-8.00	346.7
		1.27	0.58	0.22	5.57	-8.00	258.3
		1.40	0.56	0.22	5.57	-8.00	302.6
		1.38	0.56	0.22	5.57	-8.00	256.7
	06.03.2010	1.90	0.74	0.35	5.57	-5.18	310.5
		1.98	0.68	0.35	5.57	-5.18	281.8
	07.03.2010	2.50	0.51	0.51	6.03	-3.77	213.2
Van Mijen fjord	03.05.2010	3.39	0.50	0.45	3.5	-2.10	169.0
		2.13	0.48	0.40	2.7	-1.40	149.8
		2.30	0.46	0.39	2.7	-1.60	186.1
		2.27	0.45	0.37	5.7	-2.20	131.6
		3.02	0.60	0.49	3.9	-2.10	128.1
Tempel-fjorden	19.02.2011	2.53	0.58	0.49	5.78	-3.9	282.3
Advent fjord	25.02.2011	1.22	0.25	0.23	7.72	-3.2	202.0
		1.33	0.27	0.25	7.72	-3.2	160.8
Svea	21.03.2012	1.59	0.45	0.31	5.96	-2.3	193.0
		2.40	0.68	0.40	6.98	-2.0	205.0
		2.22	0.45	0.31	8.38	-2.2	178.0
	26.03.2012	3.40	0.63	0.63	4.53	-6.5	186.0
	28.03.2012	3.18	0.63	0.65	3.30	-3.3	328.0

The formula (2) has the same structure as Timco and O`Brien (1994) equation:

$$\sigma_f = 1.76 \exp(-5.88\sqrt{\nu_b})\,. \qquad (3)$$

Fig. 7 shows a curve built on Timco&O`Brien equation with a solid blue line. It can be seen that almost all ice flexural strength values measured in the Svalbard fiords are below the values produced using the proposed equation (3) when brine volume is less than 0.16 ($\sqrt{\nu_b}$<0.4).

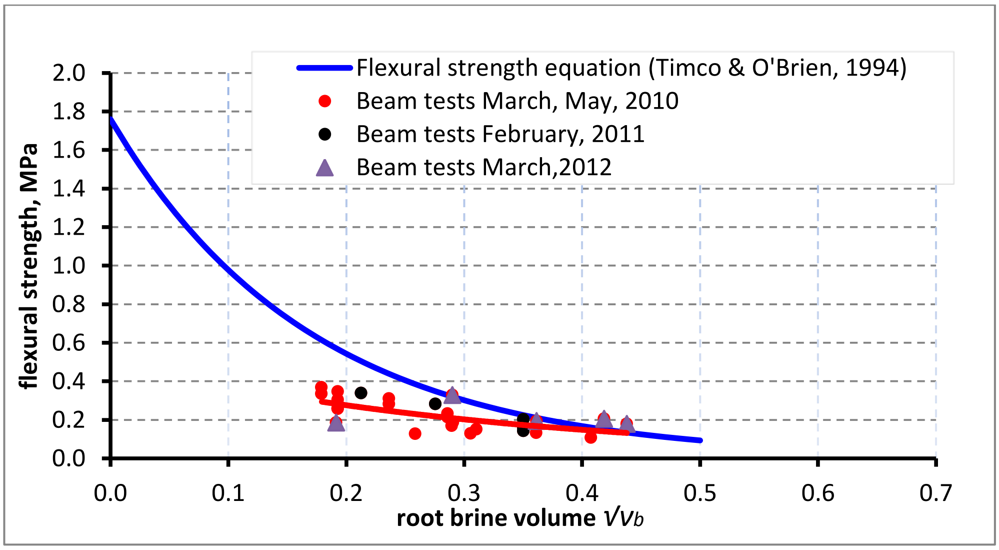


Figure 7. Experimental points of cantilever beam tests on Svalbard

Extrapolation of equation (2) out of measured ice salinity range down to null value ($\sqrt{\nu_b}$=0) gives the flexural strength of freshwater ice 0.532 MPa. This value is considerably less 1.76 MPa that is in accordance to equation (3) for freshwater ice, but is in close compliance with the freshwater ice flexural strength values that were measured on a lake near Longyearbyen: the values were in 0.504–0.601 MPa range with mean value 0.549 MPa.

The field work results are compared with some published data of sea ice flexural strength determined using the ice cantilever beam bending in other regions. The data were approximated by formulas given in Table 2.

Table 2. Flexural strength equations for various regions

Region	Equation	Source
All data	$\sigma_f = 1.76\exp(-5.88\sqrt{\nu_b})$	Timco and O`Brien, 1994
Svalbard	$\sigma_f = 0.5321\exp(-3.339\sqrt{\nu_b})$	Present paper
Okhotsk Sea	$\sigma_f = 0.8187\exp(-3.36\sqrt{\nu_b})$	Alexeev et al., 2001
Low salinity (Gulf of Finland)	$\sigma_f = 0.7\cdot(1-\sqrt{\nu_b/0.202})^*$	Bogorodsky and Gavrilo, 1980
Barents Sea	$\sigma_f = -0.346\sqrt{\nu_b} + 0.372)$	Krupina and Kubyshkin, 2007

*The formula is proposed by Bogorodsky and Gavrilo (1980) for ice containing small brine volume ($\sqrt{\nu_b}$=0.35). According to Krupina and Kubyshkin (2007), mean values of flexural strength obtained on Gulf of Finland (Baltic Sea) using cantilever beams are in good agreement with the given equation.

The equations from Table 2 are shown on Fig. 8. All the curves are below Timco&O'Brien equation at $\sqrt{\nu_b}$=0.3, and the difference is increasing with decrease of the brine volume. One of the reasons of such difference is the the equation (3) is built on the data of loading both the floating cantilever beams and small ice samples pulled out the water. This fact is noted in Krupina and Kubyshkin (2007), too.

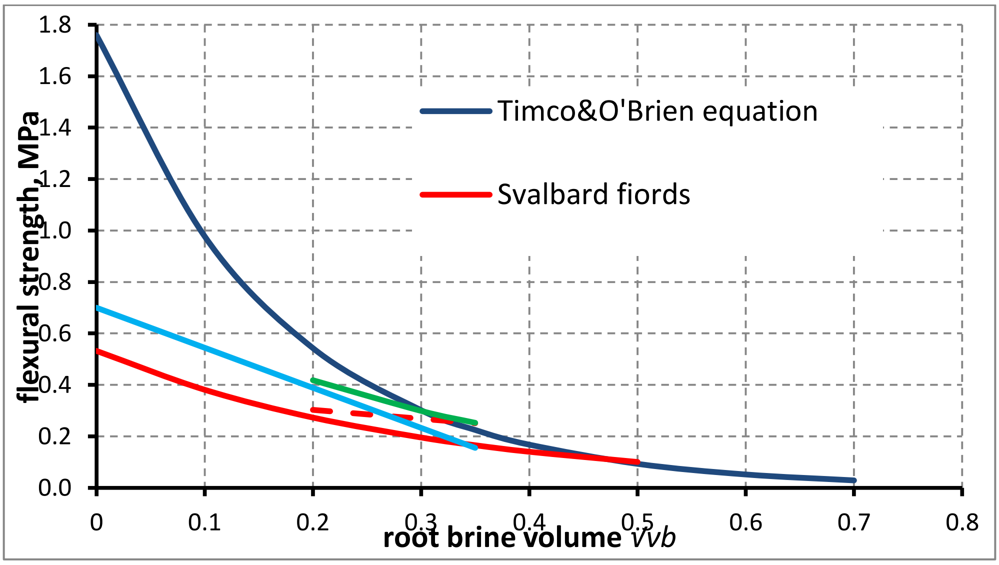


Figure 8. Flexural strength curves for various regions

Flexural strength values of ice in Svalbard fiords are close to corresponding values of Barents Sea ice that were determind during AARI expeditions in time period 1996-2006 (Krupina and

Kubyshkin, 2007).

Discrepancies between the given formulas for various regions may be caused by some differencies in the testing techniques and in the results processing. However, it seems that mostly this is because besides the temperature and salinity, the ice inner structure and deforming effect on its mechanical properties, particularly, on the flexural strength. The ice inner structure, in turn, depends on weather conditions and ice regime in specified region.

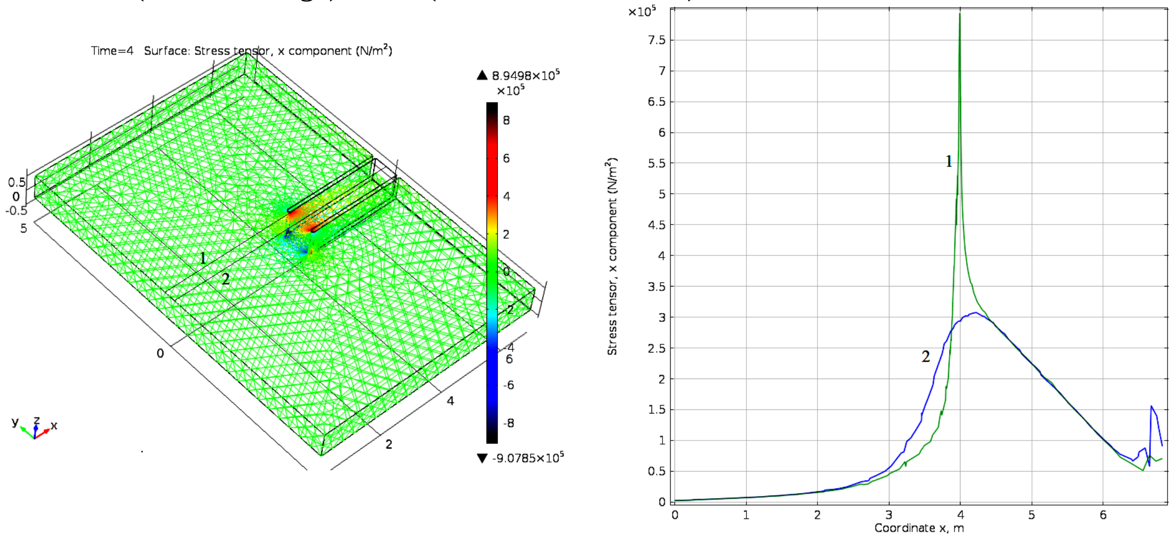
NUMERICAL SIMULATION OF THE BEAM BENDING

Svec and Frederking (1981) изучили распределение момента вдоль оси и по свободной кромке балки на основе 2D FEM с использованием plate bending elements. Here, 3D FE approach using COMSOL MULTIPHYSICS software has been applied for numerical simulation of floating cantilever beam bending.

The floating cantilever beam was cut in the plate of 10.0 m × 7.0 m. Origin of the coordinate system was in the middle of the plate thickness on the symmetry axis as it is shown in Fig. 9-a. Free end of the beam was in the same plane as free end of the plate. The vertical force was applied at a point of coordinates 7.0 m and 0.0 m. Cuts were at a distance 0.36 m from the plate symmetry axis. The cuts length was 2.83 m, and their ends were in point of coordinate 4.17 m and had semicircular form of 0.1 m diameter. The plate was resting on elastic hydrostatic foundation.

The beam dimensions were equal to corresponding values of one of the tests beams. Free end of the beam was loaded by time-linear increasing vertical force distributed along the free edge. The Young module was 2.28 GPa according to Vaudrey equation $E = 5.31 - 0.436 \cdot \sqrt{\nu_b}$.

Calculation results at time moment 4.0 s after loading start are given in Fig. 9-a as 3D stress σ_{XX} distributions, and in Fig. 9-b as stress σ_{XX} distribution along the beam axis in two sections: 1 (the beam edge) and 2 (the beam centerline).



a) b)

Figure 9.

a) FE simulation of cantilever beam bending. Coordinate system

b) Stress (σ_{XX}) distribution along the beam longitudinal axis on upper surface

Analysis of the calculation results has shown that maximal stresses σ_{xx} arise in root section of the beam, and these stresses are distributed very non-uniformly; it may be noticed significant increasing of the stresses towards the beam edges. Outcomes of this are:

- the cantilever beam breakage due to bending under loading at the free end begins in places where tensile stresses are maximal, i.e. in end points of the root section;
- the floating ice cantilever beam should be carefully prepared for bending tests: there are not allowed stress concentrators in the root section;
- the ice flexural strength values determined from the cantilever beam tests may be applied to various tasks of ice breakage due to bending with some correction.

CONCLUSION

The field investigations aimed to determine one of the crucial ice strength characteristics – flexural strength – were performed in Svalbard fiords. The main results of this work are:

- studying ice features in the fiords of Svalbard and their impact on ice characteristics;
- receiving typical values of ice flexural strength in different fiords in winter-spring season (from February to May) based on bending of cantilever beams tests;
- building dependence of the flexural strength of ice on its temperature and salinity values averaged through the ice thickness.

Comparison of resulting dependence with the formulas derived for other regions and with Timco&O`Brien equation recommended by ISO 19906 has showed:

- flexural strength values of ice in Svalbard fiords are close to corresponding values of Barents Sea ice that were determind during AARI expeditions in time period 1996-2006;
- all the curves are below Timco&O'Brien equation at $\sqrt{\nu_b}$=0.3, and the difference is increasing with decrease of the brine volume;
- besides the temperature and salinity, the ice inner structure and deforming effect on its mechanical properties, particularly, on the flexural strength;
- flexural strength equation needs to be adjusted relative to the surveyed region based on a number of large-scale bending tests of cantilever beams.

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