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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF LEVEL ICE INTERACTION WITH FOUR-LEGGED STRUCTURES

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ABSTRACT

This paper reports on work to compare the results of experiments in a model ice test tank with the theoretically calculated results for level ice interaction with four-legged structures. A numerical Finite Difference program for level ice interaction with four-legged structures had been developed in work carried out by the Saint Petersburg State Polytechnical University for BP in 2008-2009. Early results were partly published in conference papers in 2009-2010, confirming three significant factors for the process of interaction: the magnitude of the ice load, the torsion moments arising during ice/structure interaction and influence of rubble jamming between the legs. In early 2010 experiments on symmetrical four-legged structures with leg spacings of 2.5D and 6D were carried out in the ice tank of the Krylov Institute in Saint Petersburg. Two speeds and three angles of interaction were tested for each model in order to investigate ice jamming and leg sheltering. The results were normalized to the test results for a one-legged structure tested in the same ice sheet. Further analysis of the theoretical model using ice properties derived from the model tests, which is more ductile that the sea ice modeled earlier, was performed. For both leg spacings and all angles of interaction there was a good correlation between the experimental loads and moments and the theoretical loads and moments calculated using the model ice properties for the lower ice speed. These results were 20% greater than the results calculated using sea ice properties.

INTRODUCTION

In previous research projects conducted by the Saint Petersburg State Polytechnical University (SPbSPU) for BP in 2008-2009, interactions of level ice with a four legged structure were examined using a numerical Finite Difference program. The results were partly published by Shkhinek et al (2009), Thomas and Shkhinek (2009), Jasarov and Sharapov (2009). The studies suggested that three factors accompanying the process of interaction may be of great importance: the level of ice forces, torsion moments arising during the ice/structure interaction and the influence on the total load of ice rubble jamming between the legs.

The available data from experiments (Timco and Pratte, 1985, Kato and Sodhi, 1983, Kato et al 1994, Takeuchi et al) were insufficient to validate the proposed theoretical conclusions. Besides, these experiments have considered mainly the ice action on two legs and the ice moving normally to the line connecting these legs. The need for more comprehensive experimental data and detailed comparison of the theory and experiment was evident.

Therefore, the present work focused on the comparison of theoretical and experimental results.

For this purpose, model ice tank experiments were carried out in the Krylov Shipbuilding Research Institute (KSRI), St Petersburg, Russia.

A brief description of the experiments as well as the main results are presented in the paper. The comparison of theoretical and experimental data, on the whole, has showed good agreement between the results, their suitability for solving a wide range of problems and acceptability of the numerical predictions for ice loads (forces and torsion moments) on a four-leg structure from level ice.

Experimental investigations on the influence on the loads of ice rubble jamming between the legs were inconclusive due to time and distance constraints on the tests, and these results are not presented here.

BRIEF DESCRIPTION OF THE THEORETICAL MODEL

The theoretical model is based on numerical integration of equations of solid mechanics by the Finite Difference method. The following assumptions are made:

- A 2D in-plane problem is considered.
- The ice is homogeneous and elastic until the failure criterion (the Mohr-Coulomb law) is reached. After failure ice moves to the residual conditions
- Tensile failure occurs if the tensile strength is reached.
- All the strength parameters are given in proportion to the unconfined strength.
- The structure is rigid

The design scheme and considered scenario of interaction are presented in Figure 1.

The scenario corresponds to conditions when the ice is in motion. The angle α characterizes the angle between the direction of the ice motion and the line connecting the structure front legs. Some tracks form in the ice field when the ice field passes through the structure. These tracks influence subsequent interactions.

The development of interaction processes with time is considered.

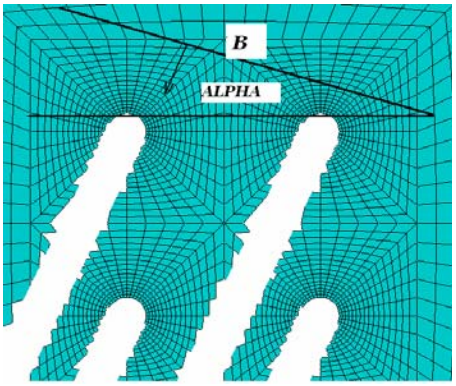


Figure 1. Scenario of interaction

CHOICE OF THE TESTS MODES BASED ON THE CALCULATIONS

The experiments were intended to cover the most interesting situations which were identified from the numerical calculation. The following problems have been checked: magnitude of the ice force, and torsion moments arising during ice/structure interaction.

Ice Forces
Figure 2 presents results from the numerical experiments conducted for BP in 2009.

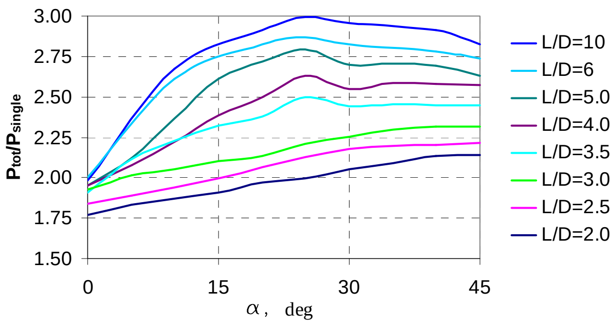


Figure 2. $P_{tot} / P_{\text{single}}$ ratio versus α

Here P_{tot} is the total force acting on the four leg structure in the moving ice; P_{single} is the force on the single leg in the same conditions; L is the distance between the centres of the legs; D is the leg diameter; α is the angle between the normal to the line connecting two adjacent legs and the direction of the moving ice.

The calculations were carried out for the conventional sea ice properties (they are given later). It follows from Fig. 2 that two factors are important for the ice force estimation: L/D and α. The influence of L/D is negligible if L/D>6 (there is no significant difference between the results at L/D=6 and L/D=10). Three angles α (0°, about 27-30° and 45°) determine the loads dependence on α. Therefore for the ice tank in the Krylov Institute experiments, angles α = 0°,(27-30)°, and 45° seemed to be most appropriate. The recommended non dimensional distances between the legs were L/D=6.0 and 2.5.

Torsion moments
Torsion moments considered in previous work are presented in Jasarov and Sharapov (2009).
Torsion moments arise due to asymmetry of the phenomenon. The asymmetry occurs when the angle α differs on 0° or 45°, or when the medium is heterogeneous or when loads reach their maximums non-simultaneously. The non-dimension torsion moment is calculated as follows

$$\overline{M} = \frac{\sum_{i=1}^{4} P_i l_i}{P_{tot} L} \tag{1}$$

where P_i is the total force acting on the leg *i* at the time when $\overline{M}$ reaches the maximum, l_i is the arm of this load. The total force on the leg is estimated as $P_i = \sqrt{(P_{ni}^2 + P_{ti}^2)}$, where P_{ni} and P_{ti} are the normal and the transversal forces on the leg *i*.

The non-dimensional moment $\overline{M}$ in the homogeneous media versus the angle α for different L/D is presented in Figure 3.

One can see that the moment is zero at α =0° and 45°, but it is not zero at α =30°. That is, important information on the moments can be derived from the model experiments.

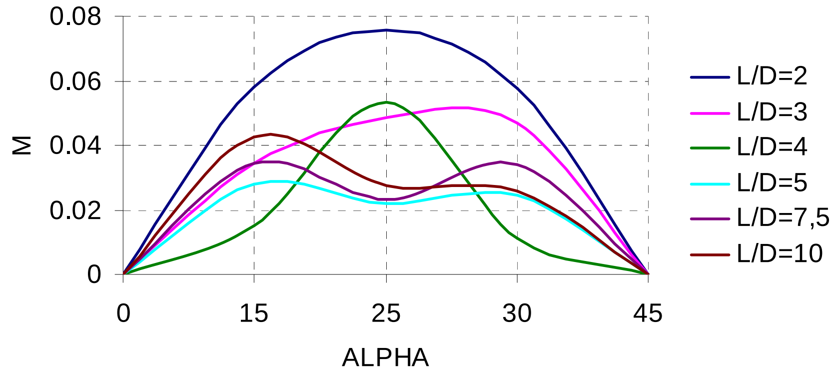


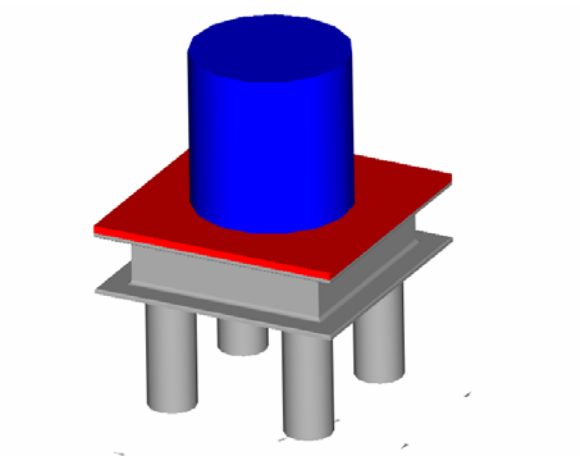
Figure 3. Torsion moments in homogeneous medium

DESCRIPTION OF THE MODEL TESTS

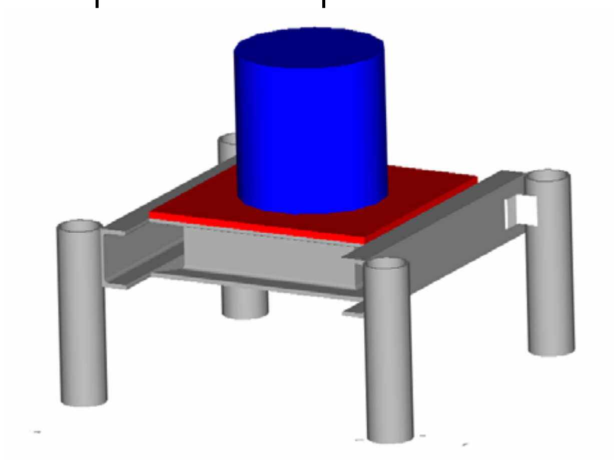
Experimental studies into interaction of four-legged structure with ice were held in the KSRI's Ice tank with main dimensions 35m×6m×1.8m, with model ice of the FG type. For the purposes of these model investigations two four-leg structure models were made fabricated with different distances between legs. The first model had L/D=2.5 and the second one had L/D=6.0. The parameters are summarized in Table 1 and the models are illustrated in Figure 4.

TABLE 1: MODEL PARAMETERS

Parameter	**Model No.1**	**Model No.2**
Number of legs	4	4
Leg diameter, m	0.077	0.077
Minimum distance between leg centers, m	0.193	0.462
Ratio of leg center distance/leg diameter	2.5	6.0



L/D=2.5



L/D=6.0

Figure 4. Four-leg structure models at various distances between the leg centres

The four-legged structure models were rigidly fixed to the towing carriage via dynamometer, and were towed during the tests through stationary level ice field. For each model, the tests were run at three angles α =0°, 30° and 45° and at two velocities 0.05 m/s and 0.01 m/s. After each set of

experiments with the four-legged model, a single leg was tested in the same model ice sheet in order to provide a reference for normalizing the results.
The forces on the four-leg model are given in coordinate axes fixed in relation to the direction of the ice flow, as shown in Figure 6. The axis X is in the direction of the ice flow.
The results of the model tests are presented in Table 2 as mean and mean peak values of horizontal ice forces and torsion moment on the four-legged structure.

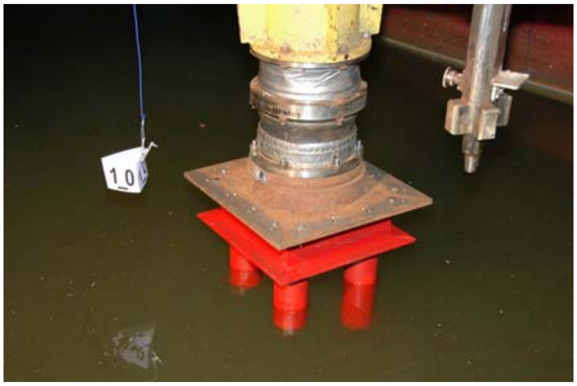


Figure 5. Four-leg structure model fixed through dynamometer to towing carriage and placed into the water before the tests

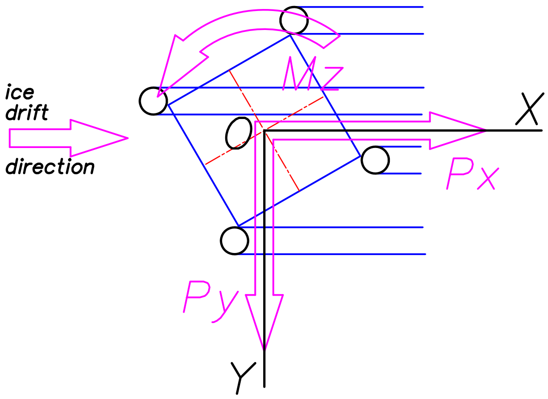


Figure 6. Coordinate axes

TABLE 2: RESULTS OF THE MODEL TESTS

Run #	**Angle [deg]**	**Velocity [m/sec]**	P_x **[N]**		P_y **[N]**		M_z **[Nm]**	
			Mean	**Mean-peak**	**Mean**	**Mean-peak**	**Mean**	**Mean-peak**
Sheet #1	**Ice thickness =33mm**		**Distance between leg centres=193mm (2.5D)**					
1_1	30	0.01	100	130	5	30	1	5.5
1_3	30	0.05	120	165	5	40	0	6.5
1_4	0	0.05	80	110	0	25	0	4.5
1_5	0	0.01	69	92	0	25	0	3.5
1_6	45	0.05	130	180	0	40	0	6.5
1_7	45	0.01	108	140	0	35	0	5.5
1_8	1 leg	0.05	46	75	0	20	0	0.5
1_9	1 leg	0.01	45	70	0	25	0	0.2

Run #	Angle [deg]	Velocity [m/sec]	P_x [N]		P_y [N]		M_z [Nm]	
			Mean	Mean-peak	Mean	Mean-peak	Mean	Mean-peak
Sheet #2	**Ice thickness =34mm**		**Distance between leg centres=462mm (6.0D)**					
2_1	0	0.01	90	120	-10	-40	-1.0	-10.5
2_4	0	0.05	110	145	-18	-53	-4.2	-16.5
2_5	30	0.05	155	195	2	35	2.0	14.0
2_6	30	0.01	125	155	1	23	1.0	12.0
2_7	45	0.05	120	147	-12	-45	-3.0	-15.5
2_8	45	0.01	105	130	-10	-35	-3.0	-14.0
2_10	1 leg	0.05	50	70	0	20	0.0	0.5
2_11	1 leg	0.01	45	65	0	23	0.0	0.3

ANALYSIS AND COMPARISON OF RESULTS

Comparison of ice properties

It is well known that the properties of sea ice and model ice (in the ice tank) are different. When planning these experiments we assumed that ice property differences would have a similar influence on the results obtained for the four legs and the single leg, i.e. the laboratory ice properties will not have a significant effect the $P_{tot} / P_{\text{single}}$ ratio.

The analysis of the model ice parameters and results suggest that ice properties may have some influence not only on the loads themselves but also on the process of interaction and four leg/ single leg loads ratio.

A comparison of sea and model ice parameters is given in Table 3.

Information about the properties of sea ice with salinity 3 ppt and an average temperature of -20 ^{0}C was taken from ISO 19906.

TABLE 3: COMPARISON OF ICE PARAMETERS

Parameter	Model ice	Sea ice
Elasticity module E, MPa	100	5000-6000
Indenter pressure (ø20mm)	40-50	–
Compressive strength σ_c, kPa	–	3800
Flexural strength σ_f, kPa	45.5	590

Analysis of the data presented in Table 3 confirms a well known fact that it is difficult to create a model ice with properties absolutely analogous to those of sea ice.

The ice properties selected for calculations of loads induced both by model ice and the sea ice can be seen in Table 4. Strength parameters are related to the compressive strength, σ_c.

TABLE 4: ICE PROPERTIES USED IN CALCULATIONS

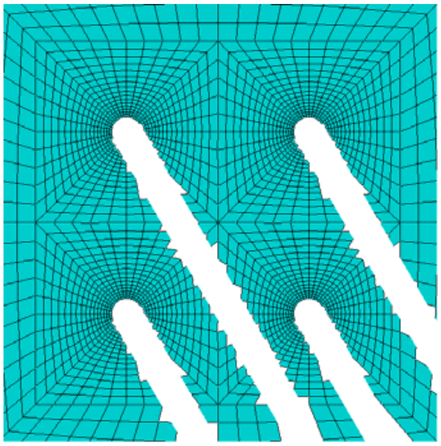
Parameter	Model ice	Sea ice
Compressive strength	1[1]	1
Tensile strength	1[2]	0.25
Residual strength	0.9	0.2
Angle of internal friction (deg)	5	30
Poisson's ratio	0.15	0.25

[1] For model ice a pressure on the indentor was accepted as compressive strength

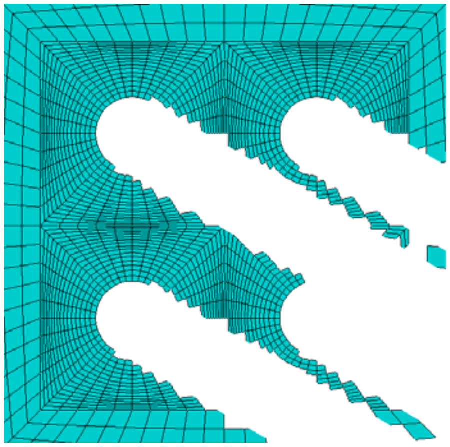
[2] Flexural strength was accepted as tensile strength

Comparison of physical pictures

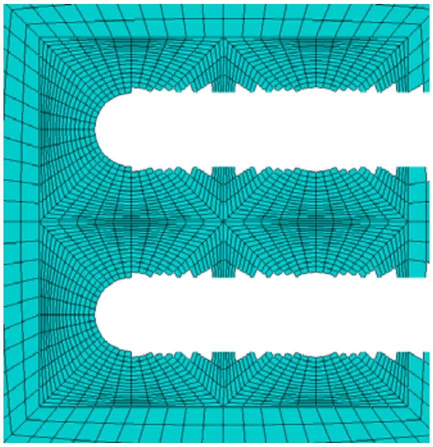
The channels formed when the structure passed through the ice were observed. A selection of results and a comparison between the theoretical results and the model tests are presented in Figure 7.



Channels formed during the structure passage through the ice (L/D=6.0; α =30°)



Channels formed during the structure passage through the ice (L/D= 2.5; α =30°)



Channels formed during the structure passage through the ice (L/D= 2.5; α =0°)

Figure 7. Experimental and theoretical pictures of interaction four-leg structure with level ice

As seen in the figures, the shapes of the channels from calculation and from the experiments are generally similar, except that in the experiments there was some accumulation of ice rubble in front of the columns which can affect the experimental results.

Comparison of ice loads (forces and moments)

For assessment of how leg geometry and interaction influence the total ice load on the four-legged structure the ratio of total horizontal longitudinal force P_x to the force on one individual leg at the same towing speed was determined. Figures 8–11 show the leg effect coefficients versus ice drift headings for the two leg spacings studied. The graphs were plotted for mean and mean peak load values. These figures contain calculation results for both model and sea ice.

In accordance with ISO 19906 the total (global) load on a multi-leg structure for the "limit stress" scenario is defined by the formula:

$F_S = k_s \cdot k_n \cdot k_j \cdot F_1$,

where

k_s – factor taking into consideration the mutual leg arrangement and shielding of after legs by forward legs,

k_n – factor taking into consideration the fact that maximum loads on legs are not generated simultaneously,

k_j – factor taking into consideration ice jamming between structure legs.

In our investigations the symbol P_x is equivalent to F_S, and the force on one leg $P_{x\,single}$ is equivalent to F_1. Then the values of leg effect coefficient obtained in these studies correspond to the product $k = k_s \cdot k_n \cdot k_j$. The experimental and calculated values of the k coefficient are presented in Table 5.

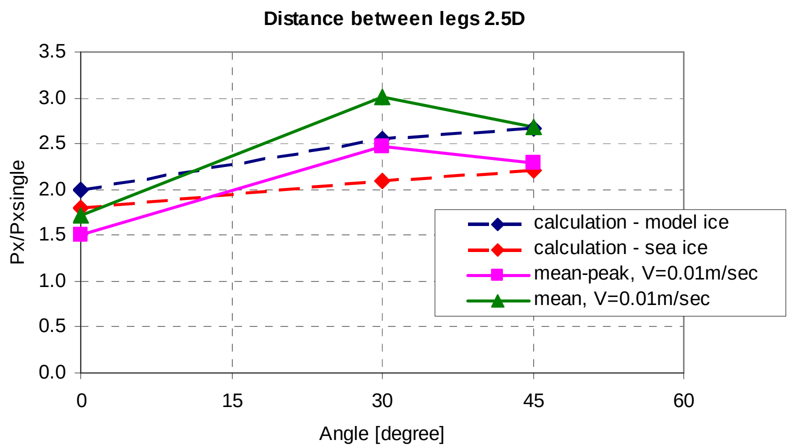


Figure 8. Ratio of total ice force on four-leg structure to ice force on one individual leg, distance between leg centers $2.5D$, speed 0.01 m/s.

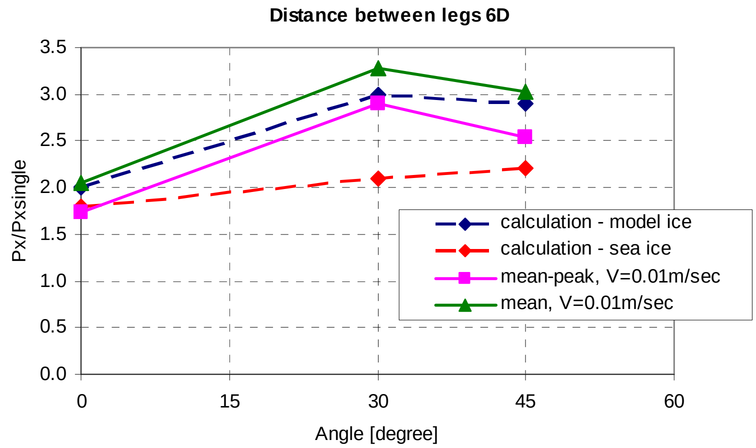


Figure 9. Ratio of total ice force on four-leg structure to ice force on one individual leg, distance between leg centers $6D$, speed 0.01 m/s.

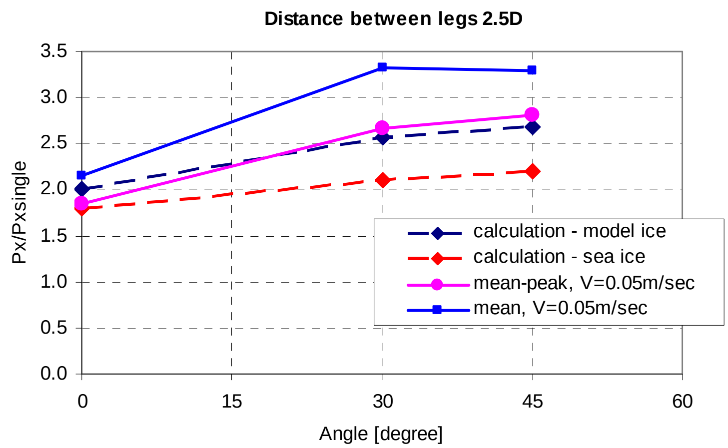


Figure 10. Ratio of total ice force on four-leg structure to ice force on one individual leg, distance between leg centers $2.5D$, speed 0.05 m/s.

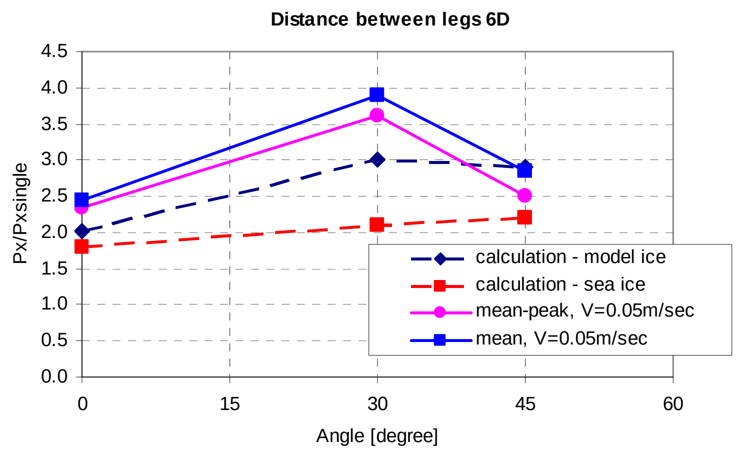


Figure 11. Ratio of total ice force on four-leg structure to ice force on one individual leg, distance between leg centers $6D$, speed 0.05 m/s.

TABLE 5: LEG EFFECT COEFFICIENTS FOR HORIZONTAL FORCE

Distance between legs	Drift angle	Calculation		Experiment			
				Mean-peak values		Mean values	
		Model ice	Sea ice	V = 0.01 m/s	V = 0.05 m/s	V = 0.01 m/s	V = 0.05 m/s
$2.5D$	0°	2.00	1.8	1.50	1.85	1.71	2.15
	30°	2.56	2.1	2.48	2.67	3.02	3.32
	45°	2.66	2.2	2.29	2.81	2.68	3.30
$6.0D$	0°	2.00	2.0	1.73	2.34	2.05	2.45
	30°	3.00	2.7	2.90	3.62	3.28	3.90
	45°	2.91	2.6	2.53	2.51	3.03	2.84

Judging by the data in Table 2, the moment determined by the mean values is zero or very low. Most likely, the moment estimates obtained in these studies are in the ranges of acceptable accuracy.

Indeed, according to Figure 2, if the angle α =30° and L/D =2.5 or 6.0, then $\overline{M}$ = 0.055 or 0.03, correspondingly. As can be seen in Table 2, the mean load levels at V=0.01 m/s are 100 N and 125 N, then the moments are M_z =1.05 Nm and 1.8 Nm, correspondingly. These results correspond to experimental data presented in Table 2.

Analysis of moments corresponding to the mean values shows that the ice was homogeneous at least over the path run by the model. This indicates that the high torsion moment corresponding to the peak value is taking place in a situation where ice failures against different legs develop non-simultaneously.

Analysis of the comparison results

In comparing analytical and experimental results one should consider that the model ice of the FG type may have a different failure mechanism from that assumed in the numerical model. Despite that possibility the experimental ice loads obtained at a slow drift speed of 0.01 m/s show quite good agreement with calculation results. This case is the most close to the conditions of analytical task, i.e. determination of maximum loads under static exposure to ice.

Experimental investigations in the ice model tank revealed that the ice load level depends on ice drift speed. On average when the speed was increased from 0.01 m/s to 0.05m/s the ice force grew by 20%.

Non-zero mean values of transverse force and torsion moment observed at 0° and 45° heading for the case with $6D$ distance between structure legs (Table 2) is associated with some inaccuracies in angle settings because even a small deviation from prescribed settings causes an interaction of the rear legs with the edges of the channel made by the forward legs.

Another reason for the occurrence of transverse loads is in the non-simultaneous failure effect considered above.

It is seen from Table 5 that in a number of cases the experimental values of leg effect coefficients exceed 2.0 at drift angle 0°. It is observed at higher speed of 0.05 m/s. Apparently, the speed influences the interaction between legs and ice blocks in channel. In addition, as it was mentioned above, in the case with the $6D$ distance between structure legs even a small error in angle setting causes interaction of the rear legs with the edges of channel made by the forward legs, which causes an increase in the total load on structure.

CONCLUSION

1. It was found that the model ice used in these experiments is more ductile than sea ice. As pointed out in previous observations (e.g. Blenkarn 1970) loads from warm (ductile) ice are higher than those from the brittle ice. The approximate parameters for the FG model ice used in our calculations have confirmed these observations. Interactions of the stress field around the legs in a ductile medium are about 20% higher than in brittle ice.
2. The experimental investigations in the ice model tank have revealed that the ice drift speed influences the ice load level. On average when the speed is increased from 0.01 m/s to 0.05m/s the ice load grows by 20%. The explanation, and the possibility that this phenomenon could transfer to full scale conditions needs more detailed consideration
3. There is a good correlation between theoretical and experimental results for velocity V=0.01m/s. With V=0.05m/s, the correlation is not as good. The explanation has not be quite clear yet. Probably this is connected with the model ice properties and details of ice/structure interaction.
4. The mean loads (and especially moments) are more stable than the mean peak moments and forces. The peaks are random and are probably caused by non-simultaneous ice failure against different legs.
5. In conclusion, the correlation obtained between theory and experiments is validated as acceptable for these model tests, showing that the proposed theoretical solution may be a useful tool in the study of the processes occurring during full-scale ice/structure interaction in sea ice.

AKNOWLEGMENTS

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