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Level ice interactions with multi-legged offshore structures

Воздействия ровного ледового поля на многоопорные гидротехнические сооружения

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Ключевые слова: многоопорные сооружения; ледовая нагрузка; численная модель; ANSYS; взаимовлияние опор

Abstract. The task of determining the total ice load from drifting level ice floes on 3- and 4-legged structures, widely used in the development of offshore oil & gas fields, was considered in the article. The ANSYS numerical 3D model was used to investigate how the total ice load is influenced by various factors, including the thickness of ice, the leg spacing, the ice drift direction in relation to the structure, the presence of jammed ice between the legs. Based on the results of numerical analysis, a comparison was made between the 3- and 4-legged structures in terms of magnitude of ice load, as well as additional recommendations were done for the procedure of total ice loading calculation in accordance with the Russian national code.

Аннотация. В статье рассмотрены задачи определения суммарной ледовой нагрузки от ровного ледового поля на 3-х и 4-х опорные сооружения, широко применяемые при разработке морских шельфовых месторождений. При помощи численной 3D модели в программе ANSYS было проанализировано влияние на суммарную ледовую нагрузку различных факторов, в том числе толщины льда, расстояния между опорами, угла дрейфа льда относительно сооружения, наличия затора ледовой массы в пространстве между опорами. На основе результатов численного моделирования было проведено сравнение 3-х и 4-х опорного сооружения с точки зрения величины ледовой нагрузки, а также представлены дополнительные рекомендации к расчету суммарной ледовой нагрузки по отечественным строительным нормам.

Introduction

Among the offshore structures there are both single- and multi-leg structures. The quantity, location and distance between them depend on specifics of the structure, its functional purpose and the loading combinations perceived by each leg. Several examples of multi-legged structures are shown on Figure 1.

a) b) c)

Figure 1. Examples of multi-legged offshore structures: a) four-legged offshore oil & gas platform; b) multi-span bridge; c) LNG Jetty

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The task of effective design of multi-legged offshore ice-resistant structures in the waters of northern seas is of ultimate importance now days, and accuracy of determining the ice loads directly affects the material consumption and the final cost of the structure, as well as the operation safety.

The total ice load on a multi-legged structure is determined, as a rule, according to the principle:

Total ice load = number of legs × leg factor × individual leg load.

And according to the Russian Set of Rules SP 38.13330.2012 "Loads and impacts on hydraulic structures" [1], the total load is determined by the formula:

$$F_{total} = n_t K_1 K_2 F_1, \tag{1}$$

where n_t– number of legs; F_1 – ice loading on 1 leg; K_1, K_2 – factors, taking into account non-simultaneous peak loads on individual legs and the shielding effect of adjacent legs accordingly.

After determining the individual ice load per one leg, F_1 (which is a separate task and not considered in detail in this paper), the key issue is consideration of factors that influence the total ice load on a multi-legged structure, namely:

$$F_{total}/F_1 \tag{2}$$

$$\text{or } n_t K_1 K_2 \tag{3}$$

Among the main known factors are the following:

1) mutual influence of legs and leg shielding;

2) non-simultaneous occurrence of load peaks on different legs;

3) probability of ice rubble jamming between the legs.

The influence of the *first* and *second factors* is difficult to track separately. Therefore, their joint influence on the total ice load is usually considered. At the moment, there is a limited number of works presented at various international conferences [2-5], where this theme was highlighted. They all considered 4-legged structures only. The main conclusion of the works was the fact that the ratio F_{total}/F_1 depends on the following main factors:

$$F_{total}/F_1 \sim \alpha;\ L/D \tag{5}$$

where α – is an impact angle of drifting ice in relation to the structure. It was justified that the maximum total ice load on the 4-legged structure takes place when the structure is exposed to the ice drift at the angle of 20-30˚ relative to the horizontal axis of the structure;

L/D - is the ratio of the leg spacing L, m, and the leg diameter D, m. At the same time, different works gave different dependency of F_{total}/F_1 as a function of L/D. In some papers it was said that F_{total}/F_1 is not influenced by L/D variation at L/D>6 [2], in others at L/D>12-20 [3-5].

Another conclusion from the previous works was the fact that, depending on conditions, F_{total}/F_1 for the 4-legged structure may vary in the range of 2-3.5.

Nevertheless, in these works the influence of ice thickness on F_{total}/F_1 was not disclosed, the physics of ice interaction with shielded backside legs depending on α was not fully disclosed, and there was no consistency in certain results. Thus, the need for further research on this issue is evident.

A number of sources [6-8], including the international standard ISO 19906 [8], indicate the need to take into account the *third factor*, the probability of ice jamming in between legs, in the form of an additional coefficient K_{jam} (when L/D <4). At the same time, none of the sources give any specific recommendations on the value of the coefficient. Further studies are needed to justify the coefficient.

Therefore, the main goal of the research was to check the magnitudes of leg factors with the help of numerical modelling and to give certain recommendations for magnitude of the third factor, namely ice jamming factor. The supplementary goal was to check which of the two structures, 3- or 4-legged, perceive less loading from level ice in ice-infested waters.

To achieve these goals the following was done:

1. A 3D numerical model for the level ice was created in ANSYS;

2. Investigation of how F_{total}/F_1 is influenced by the drifting ice impact angle α, the thickness of the ice *h* and the leg spacing L/D;
3. Analysis of physics of ice field – structure interaction process when ice rubble is jammed and consolidated in between the legs. Estimation of the possible increase in ice loading due to this effect;
4. Comparison of 3 and 4- legged structures in terms of ice loading magnitude.

Methods

The study was carried out by numerical simulation in the ANSYS Explicit Dynamics program. In order to study the ice field – structure interaction process, a specially developed numerical 3D model was used, for which the following assumptions had been done:

1) ice was regarded as a solid body;

2) the brittle fracture of ice was considered at relatively high deformation rates. It's assumed that before the brittle failure, the ice behaves in elastic mode under loading. To describe the mechanical behavior of ice under load, the Mohr-Coulomb model was used, in which the strength of ice depended on the lateral pressure, and the compressive strength was an order of magnitude higher than the tensile strength, which corresponds to the actual behavior of ice under load described by many sources [11-13]. Table 1 presents the basic characteristics of the model ice, adopted based on analysis of different Russian and foreign sources [14-17]. The Mohr-Coulomb model had been previously used by other researchers to describe ice behavior [18-21];

3) brittle fracture in dynamics was taken into account by removing individual finite elements (by Element Erosion technique). As a criterion for destruction, the principal normal deformations were assumed;

4) the hydrostatic and hydrodynamic effects of water were not taken into account;

Table 1. Basic physical and mechanical data of the model ice

Density, kg/m3	900
Elastic modulus, MPa	3000
Poisson's ratio	0.3
Angle of internal friction, ˚	30
Cohesion coefficient, MPa	1.0
Maximum principal strain	0.001

Verification of the numerical model was carried out by comparing the simulation results with the results of two experimental studies:

1. Indentation of rectangular horizontal stamp in ice field (full-scale tests in the Sea of Okhotsk, 1998, [9]);

2. Laboratory model tests of ice field interaction with 4-legged structure, 2011, [2].

As verification showed, the numerical model yielded results close to actual conditions. Figure 2 shows that the numerical model accurately reproduces the character of ice load oscillations in time, which was noticed during field trials in the Sea of Okhotsk [9], when the peak load was due to initial contact, and the subsequent load was only 20-80% of the initial load. Figure 3 shows that the nature of the legs penetration through the ice field by numerical modeling and during model tests in the Krylov Research Center [2] actually coincides.

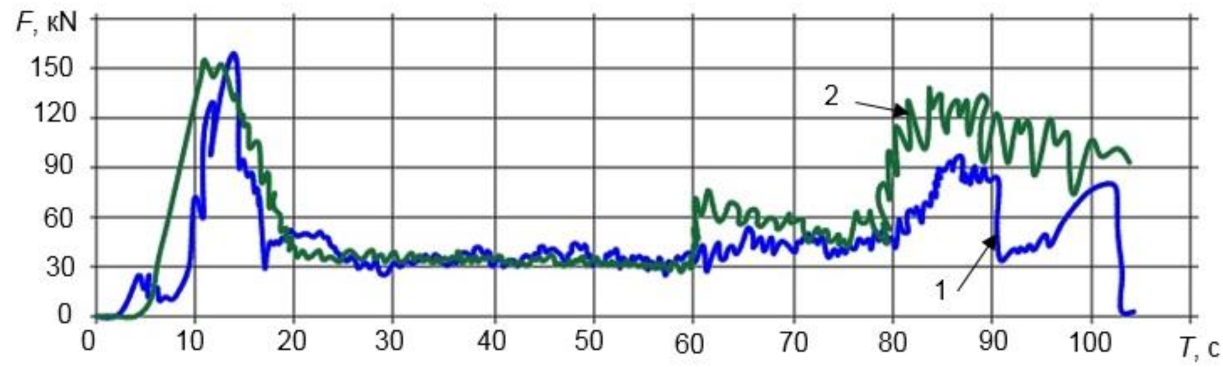
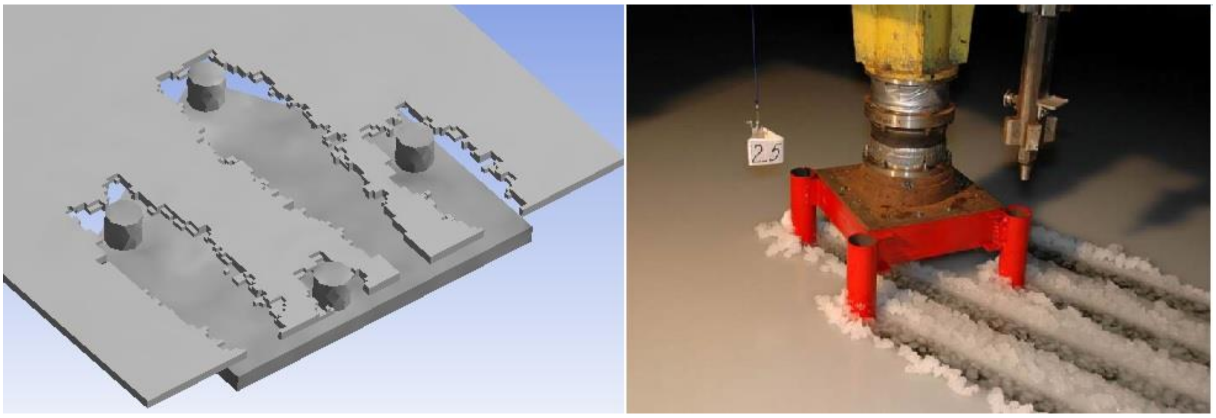


Figure 2. Graph of ice load oscillations during the stamp indentation experiment:
1 – during the field works; 2 – during the numerical modelling [10]



a) **b)**

Figure 3. The picture of 4-legged structure penetration in the ice field when $\alpha = 30°$:
a) during numerical modelling; b) during model tests in the basin

Results and Discussion

In order to investigate the mutual influence of adjacent legs on the total ice load, numerical modeling was carried out for a number of scenarios, namely, for L/D = 3; 4.5; 6; 8 at the drifting ice impact angles α = 0; 15; 22.5; 45˚ for 4-legged structures and at α=0; 15; 30; 60˚ for 3-legged structures. The thickness of ice was taken h = 0.5 m and 1.0 m. The results of numerical modelling are presented in Table 2 and Figures 4, 5 for 4-legged structures, in Table 3 and Figure 7 for 3-legged structures.

Table 2. Results of numerical analysis of mutual influence of legs of the 4-legged structure on the total ice load in the form of F_{total}/F_1.

	0˚	15˚	22.5˚	45˚
h = 0.5 m (D/h = 6)				
L/D = 3	1.9	2.4	2.6	2.6
L/D = 4,5	1.9	2.7	2.9	2.7
L/D = 6	1.9	2.9	3.1	2.7
L/D = 8	1.9	3.0	3.2	2.8
h = 1.0 m (D/h = 3)				
L/D = 3	1.9	2.9	3.1	2.8
L/D = 6	1.9	3.2	3.4	2.8

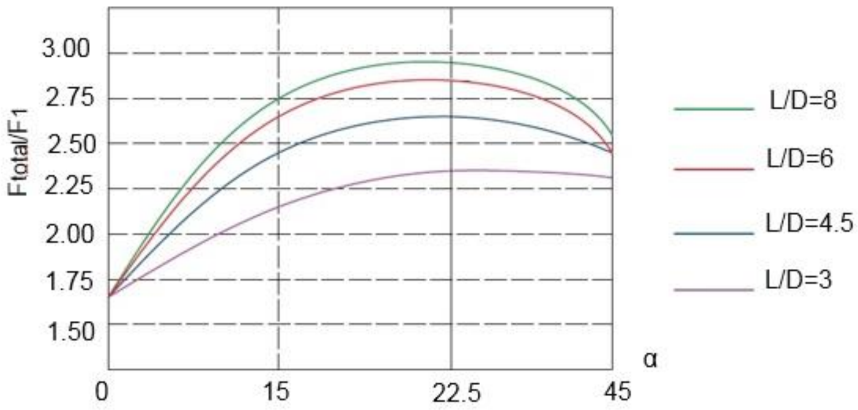


Figure 4. The graph of dependence of F_{total}/F_1 on the leg spacing and ice drift impact angles (for ice thickness h=0,5м) for the 4-legged structure

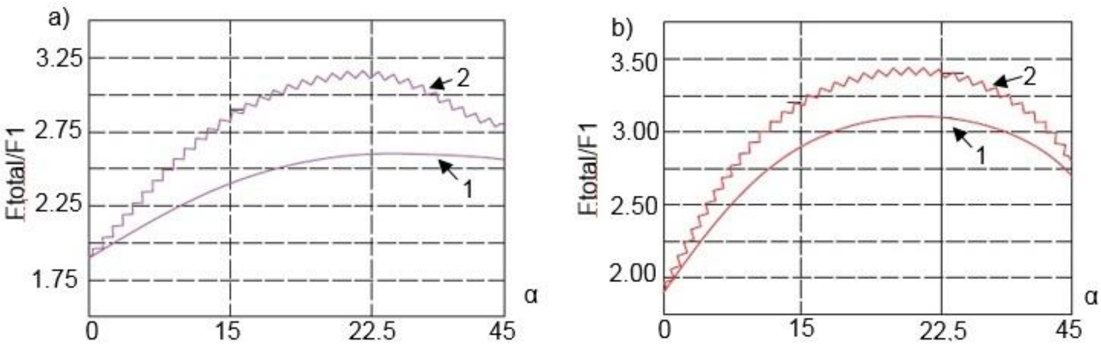


Figure 5. Graph of ice thickness influence on F_{total}/F_1 at:
a) *L/D*=3; b) *L/D*=6; 1–h=0,5m; 2– h=1m

From Table 2 and Figures 4, 5 it can be seen that:

- for the 4-legged structure (when ice thickness h = 0.5 and h = 1.0 m) the ratio F_{total}/F_1 = 1.9-3.4, which, in general, corresponds with the previously declared results by other researchers;
- the peak load was observed when the ice acted on all four legs and when the second row of legs was not in the shadow of the front legs (fully or partially), that is, when the angle of impact was in the range 20-30˚ (Figure 5).
- the ratio F_{total}/F_1 as a function *L/D* did not change significantly for *L/D* = 6 and *L/D* = 8. As a result, it can be assumed that for *L/D*> 8 F_{total}/F_1 will not be influenced by *L/D* increase. This result is higher than 6 from [2], but less than 12-20 from [3-5].
- the thickness of ice, or the ratio *D/h*, has a large influence on F_{total}/F_1, which is clearly showed on Figure 5. This is because, under certain conditions, ice will break down on contact with the second row legs not in compression, but as a result of loss of stability, as depicted in Figure 6a.

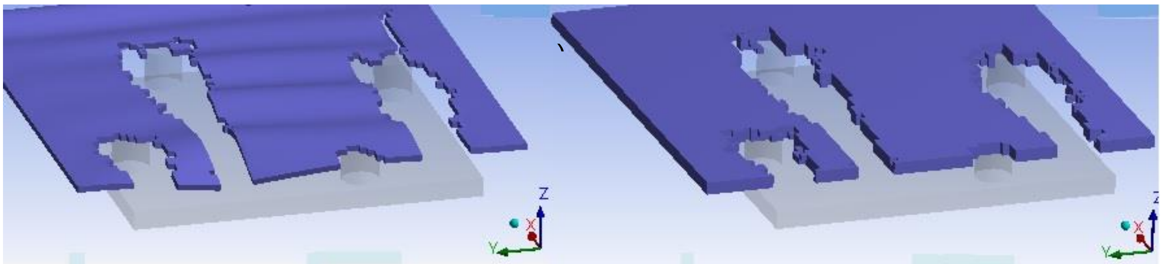


Figure 6. Nature of structure legs penetration through the ice field at L/D=6, α=22.5˚:
a) h = 0.5 m; b) h = 1.0 m

Table 3. Results of numerical analysis of mutual influence of legs of the 3-legged structure on the total ice load in the form of F_{total}/F_1.

	0˚	15˚	30˚	60˚
h = 0.5 m (D/h = 7) at D = 3.5 m				
L/D = 3	2.6	2.3	1.9	2.5
L/D = 4.5	2.7	2.4	1.9	2.6
L/D = 6	2.7	2.5	1.9	2.7
L/D = 8	2.8	2.6	1.9	2.7
h = 1.0 m (D/h = 3.5) at D = 3.5 m				
L/D = 3	2.8	2.4	1.9	2.7
L/D = 6	2.9	2.7	1.9	2.9

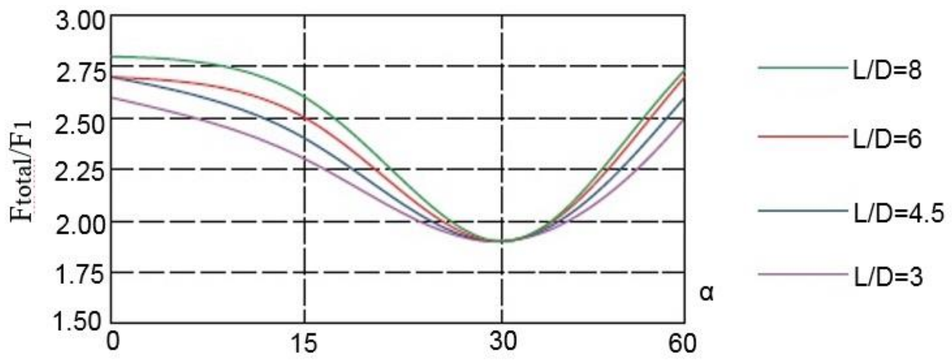


Figure 7. The graph of dependence of F_{total}/F_1 on the leg spacing and ice drift impact angles (for ice thickness h=0,5м) for the 3-legged structure

Analyzing the results for 3-legged structure, shown on Table 3 and Figure 7, it can be concluded that, depending on the ice drift impact angle on the 3-legged structure, the ratio F_{total}/F_1 can vary in the range 1.9-2.9. The smallest load occurs when the third support is completely or partially in the shadow of the front support. Reduction of the total load, as well as in the case with the 4-legged structure, may happen due to increased flexibility of level ice (at *h* ≤ 0.5 m).

The numerical analysis showed for the 4-legged structure that in some cases the presence of jammed ice mass inevitably leads to an increase in the total ice load, namely, at the drifting ice impact angles close to α = 0 ° and α = 45 °, as shown on Figure 8. It can be seen that the load from the impact of level ice field is transferred to shadow supports through the jammed ice mass. But, in case when there is no jammed ice, these legs remain untouched. The additional load will depend on the strength of the jammed ice mass. But taking into account the reduced strength of jammed ice comparing to level ice, the simulation results give an increase in the total load by 15 % and 10 %, respectively.

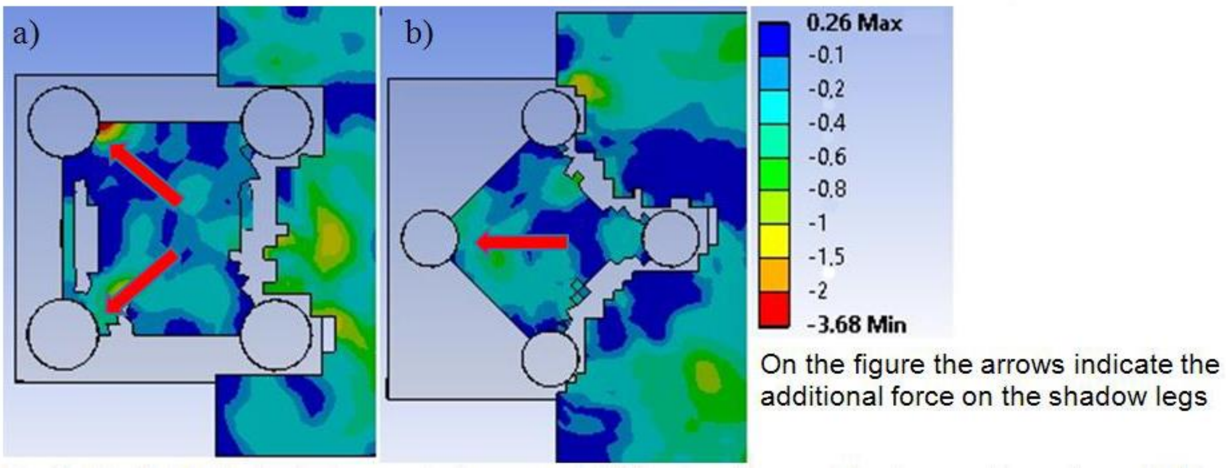


Figure 8. The field of principal normal stresses of drifting level ice and the jammed ice: a)$\alpha = 0°$; b)$\alpha = 45°$.

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On Figure 9 there is a picture of ice impacting structure at α = 22.5 °. It can be seen that for three frontal legs, the nature of ice impact does not actually change (as for the case without ice jam). On the 4th backside leg, the ice field acts through the jammed ice mass. Strength and thickness of the ice mass will determine the load on this support. But the numerical simulation showed, that increase in the total load in this case will be not significant. Table 4 presents the values of the total ice load on the 4-legged structure at *L/D* = 3, considering the presence of ice jammed mass and it's absence (for comparison).

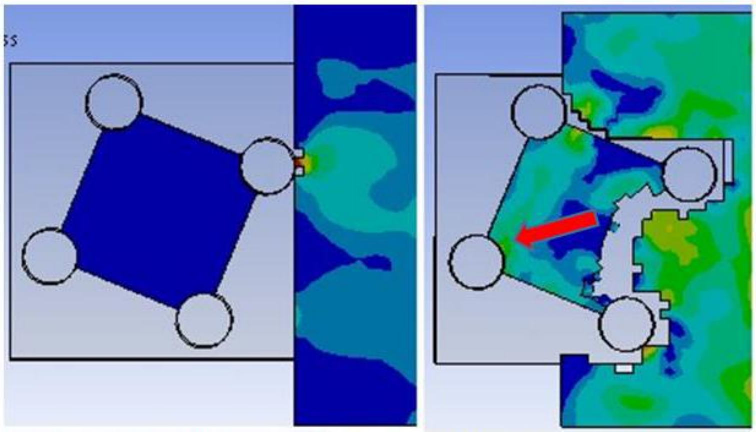

Figure 9. The field of principal normal stresses of drifting level ice and the jammed ice in case of ice field impacting the 4-legged structure at angle $\alpha = 22.5°$

Table 4. Values of the total ice load on 4-legged structure for the jammed ice situation and its absence

	$\alpha = 0°$	$\alpha = 15°$	$\alpha = 22.5°$	$\alpha = 45°$
No jammed ice	2.5 MPa	3.1 MPa	3.4 MPa	3.4 MPa
Jammed ice	2.85 MPa (+ 15 %)	3.25 MPa (+ 5 %)	3.47 MPa (+ 2 %)	3.75 MPa (+ 10 %)

Based on results, it is possible to confirm the validity of introduction of an additional coefficient to account for the effect of ice jam, which is proposed by some sources and standards [6-8], when determining the total ice load on the 4-legged structure at *L/D* < 4. The value of this coefficient should be justified for individual cases, but as numerical study show, the presence of consolidated ice jam can increase the total ice load by no more than 10%. Thus, the coefficient can be taken as K_{jam}=1.1.

For the 3-legged structure the results of the numerical simulation did not show any significant increase in the load. It can be seen on Fig. 10 that the transfer of the compressive forces from the ice field to the backside leg through the ice jam takes place along the length *S*, which is comparable with the diameter of leg - *D*. At the edges of the ice jammed mass, tensile stresses arise which cause a rapid collapse of ice. Thus, the jammed ice factor for 3-legged structures in most cases can be neglected.

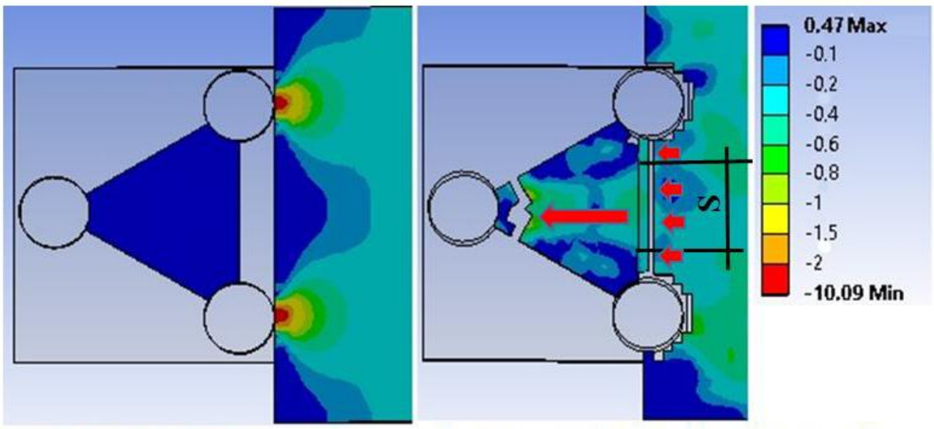

Figure 10. The field of principal normal stresses of drifting level ice and the jammed ice in case of ice field impacting the 3-legged structure at angle $\alpha = 0°$.

As the last point of the current research, the 3- and 4-legged structures are compared in terms of the magnitude of total ice load. Two situations are considered: *L/D* < 4 - when the ice jam present, *L/D* > 4 – no ice jam. The results are applicable for an ice thickness of up to 1 meter, which was considered in the numerical study.

Situation 1. *L/D < 4* (presence of ice jam).

As the numerical study showed for the 4-legged structure (Table 2), the maximum value of ratio F_{total}/F_1 for the case of $\alpha =$ 22.5 and *L/D* < 4 was 3.1. Taking into account the effect of ice jam, $K_{jam} = 1.1$, leg diameter *D*=3m and thickness of ice *h*=1m, the total load is determined as following:

$$F_4 = 3.1F_1 \cdot K_{jam} = 3.1 \cdot p_{ice} \cdot 3 \cdot 1 \cdot 1.1 = 10.23p_{ice}, \quad (6)$$

where p_{ice} – effective pressure of ice (for the study intentionally considered the same for 3- and 4-legged structures).

The total load on the 3-legged structure is determined taking into account the fact that the maximum value of F_{total}/F_1 for the case α = 0˚ and *L/D* < 4 was 2.8 (Table 3), $K_{jam} = 1.0$, diameter of the support *D* = 3.5 m, thickness of ice *h* = 1 m:

$$F_3 = 2.8F_1{}^{/} \cdot K_{jam} = 2.8 \cdot p_{ice} \cdot 3{,}5 \cdot 1 \cdot 1.0 = 9.8p_{ice} \quad (7)$$

As it can be seen from the calculation results, the difference in the ice load is minimal.

Situation 2. *L/D > 4* (no ice jam).

Following the same procedure, as in the first Situation, the total ice loads are determined for the situation when *L/D>4* and ice jam is not present:

$$F_4 = 3.4F_1 = 3.4 \cdot p_{ice} \cdot 3 \cdot 1 = 10.2\, p_{ice} \quad (8)$$

$$F_3 = 2.9F_1{}^{/} = 2.9 \cdot p_{ice} \cdot 3{,}5 \cdot 1 = 10.15\, p_{ice} \quad (9)$$

As it can be seen, the ice load on the 4-legged structure is only slightly higher than the same load on the 3-legged structure. Thus, when choosing one of the two types of structures, other from ice load magnitude criteria will come to the fore, such as the convenience of transportation and construction, the weight of the structure, the layout of the deck, and others. At the current moment the preference is mostly given to 4-legged structures. Though, some researchers, like Vershinin S.A. [14], mentioned that 3-legged structure might be more efficient in ice-infested waters.

Conclusions

1. The results of numerical study showed that mutual influence of adjacent legs on the total ice load is determined by the following factors:

– ice impact angle: for both 3- and 4-legged structures, the biggest ice load is noticed when the second row legs are not shielded by the front legs (fully or partially). For the 4-legged structure this angle is in the range 20-30˚ (as on Figure 6), for the 3-legged structure - when ice initially hits 2 legs (as on Figure 10);

– the leg spacing: as the study showed, F_{total}/F_1 will not be significantly influenced by *L/D* when *L/D* > 8;

– ice thickness *h* (or *D/h* ratio): the thickness of ice implies a significant effect on F_{total}/F_1 and on the total ice load as a result. In case of sufficient flexibility (at *h* ≤ 0.5 m, *D/h* ≥ 6), the ice, acting on the legs of the second row, may break down by loss of stability, rather than in a crushing mode. Thus, based on the numerical simulation results for relative thin ice (*h* ≤ 0.5 m, *D/h* ≥ 6) for the 4-legged structure, the effect of mutual influence of adjacent legs gave the maximum result of F_{total}/F_1 - 3.2; for thicker ice (*h* ≤ 1.0 m, *D/h* ≥ 3) – 3.4. Accordingly, for the 3-legged structure for thin ice (*h* ≤ 0.5 m, *D/h* ≥ 7) - 2.8; for thicker ice (*h* ≤ 1.0 m, *D/h* ≥ 3.5) - 2.9.

2. Regarding the ice jamming effect on the total ice load, the numerical study showed the validity of introducing an additional coefficient accounting for the effect of ice rubble jam in between legs of structure, which is proposed by some sources and standards [6-8], when determining the total ice load on the 4-legged structures at *L/D* < 4. The value of this coefficient should be

justified for each individual case, but as the simulation results showed, the ice jam effect should not increase the total ice load by more than 10 %. Thus, the coefficient can be taken as K_{jam}=1.1.

3. The numerical study showed (when the ice thickness is up to 1 meter) the ice load on the 4-legged structure is only slightly higher than the same load on the 3-legged structure. So, when choosing one of the two types of structures in this case, other criteria, such as the convenience of transportation and construction, the weight of the structure, the layout of the deck, and others will come to the fore.
4. The following provisions should be regarded when estimating total ice loads on 3- and 4-legged structures according to Russian standard [1]:

– since the total ice load depends on various factors, including the ice thickness, leg spacing and drifting ice impact angle, coefficients K_1 and K_2 need to be refined for each individual case by numerical and physical modeling. Nevertheless, the results of the numerical study yielded the values of $n_t K_1 K_2$ close to that, which Russian Set of Rules SP 38.13330.2012 might give, namely 3.4-3.5 for the 4- legged structure. For the 3-legged structure the calculated value of $n_t K_1 K_2$ by Russian Set of Rules SP 38.13330.2012 will yield a result of 2.6-2.7, which is less than the result of the numerical study, which is 2.8-2.9. Therefore, for 3-legged structures, calculations according to the Standard might yield underestimated results, which should be taken into account;

– when there is a possibility of ice rubble jamming and it's consolidation in the space between legs of the structure (as a rule, at *L/D* < 4), it is recommended to introduce an additional coefficient of jammed ice K_{jam}, equal to 1.1 for the 4-legged structures.

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