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Study of Specific energy of mechanical destruction of ice for calculation of ice load on ships and offshore structures

Tsuprik V.G.†

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Abstract: Analysis of scenarios of transportation oil and gas which produced in the Arctic and others cold seas shows that in the near-term there will be a significant increase of tonnage of tankers for oil and gas and number of ships which should be exploited in difficult ice conditions.

For the construction of ice-resistant structures (IRS) intended for production of oil and gas and transportation of these products at ice-class vessels, calculating the load from ice to board the ship and on surface of supports of the platforms are the actuality and urgent tasks. These tasks have one basis in both cases: at beginning of the contact occurs fracture of edge of ice, then occurs compressing of rubble shattered of ice, then they extruding from contact area, after this next layer of ice begin to destruct. At calculating the strength of plating and elements construct of vessels, icebreakers and ice-resistant platforms the specific energy of mechanical destruction ice ϵ_{cr} is an important parameter.

For the whole period of study of physical and mechanical characteristics of sea ice have been not many experimental studies various researchers to obtain numerical values of this energetic characteristic of the strength of ice by a method called Ball Drop Test.

This study shows that the destruction of the ice from dynamic loading in zone of contact occurs in several cycles, and the ice destructed with a minimum numerical values of ϵ_{cr}.

The author offer this energy characteristic to take as a base value for the calculation of ice load on ships and offshore structures.

Keywords: Arctic shelf; ice load; fracture of ice; specific energy destruction the ice;.

1. Introduction

The problem of rationing the strength of ship hulls from ice loads originated in the late 19th century in connection with the construction most powerful of the world's icebreaker "Ermak" in Russia. Initiators of construction, first researchers and constructors this project were famous at that time Professor D.I. Mendeleyev, Admiral S.O. Makarov and academician-shipbuilder A.N. Krylov, who directed the first pool for testing ship models. But, despite an wide knowledge of these scientists which have developed the first technical specifications for the construction of an ice-breaker, the strength of his hull has been insufficient for laying channels in conditions of the polar ice cap, because the experience for design of ships of this class at that time virtually was absent. Of course, this fact no way diminishes the merit of these scientists, but only underscores the difficulty facing shipbuilders.

† Corresponding author: School of Engineering, Far Eastern Federal University, Vladivostok, Russia, E-mail: tsuprik.vg@dvfu.ru, Tel: +7 9241212374

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With the beginning of the development in the 30-ies of last century the Northern sea route and intensive construction of the ships and the icebreaker for this purpose in the USSR received development the theoretical research of strength hull of ships and in 50-ies was formed a theoretical principles descriptions impact of ice force on the ship hull. In the year 1956 in the USSR approved the “Rules for classification and construction of sea ships”. These "Rules..." based on the method of “conditionals the instruments-measuring of quality resist of ships from ice load” and they not used parameters of ice strength explicitly, were only possibilities to compare the strength of hull of different vessels, taking into account their constructions and operating experience. The next stage of development of the science of ice strength of ships in the USSR was been as realization the extensive program measurement of strain constructions of hulls real ships and icebreakers different series from ice loads. Such studies, since 1963, were conducted annually by the laboratory staff of qualities ships of the Arctic and Antarctic Research Institute (AARI) D.E. Kheisin, V.I. Kashtelyan, V.A. Lihomanov, Yury Popov, Alexander Fadeev, O.V. Rivlin, etc. The results of these studies have defined the numerical values of voltages that occur in a side set and cladding, as well as show the shape and size of the contact patch. In the same period, in the calculation of ice load appeared some numerical estimates of physical-mechanical properties of ice.

By the mid 1960 – 1970 y.y. as a result of the work of scientists and specialists of the AARI was developed fairly slender methodology Popova-Kheisina of the theoretical definition of ice loads. The basis of this theory were model non-central hitting the by ice floe to board of ship, which the most fully developed Y.M. Popov, and model the local crushing of ice edge when hitting a solid body, proposed by D.E. Kheisin **[2]**. According to this model, the ice pressure may not exceed the tensile strength to the local crushing (fragmentation) of the latter. In 1967 was published a monograph "Resistance vessels navigating in ice" **[3]**, in which summarizes the contemporary experience of theoretical and experimental research of ice strength of the ships. Study of ice strength of ships have developed in different countries, but noted monograph remains the only major generalization of results of research on the subject.

2. Models of breaking the ice for practical calculations of ice loads

As the basis of its physical model Kheisin D.E. took model of impact on a solid barrier the body, which moving at speed v, and the material which has properties of viscous fluid with density ρ. Pressure on contact in this case are determined by the formula of high-speed pressure $p=\rho v^2$. Assuming that the kinetic energy of a moving body will be fully spent on its destruction ($\epsilon_{cr}=v^2/2$), the author of this hypothesis suggested by analogy to use this method to define a contact pressure of ice on board the vessel. He accepted that "the movement of the will continue until the contact pressure ρ exceeds the pressure p_k with is still required for breaking the ice." Pressure p_k, distributed on an area of contact, to determining the load onboard of vessel to a first approximation to take as strength of ice on local fracture of ice. For determining "effective" value of the strength of the author suggested the use of the specific energy of "mechanical crushing ice" ϵ_{cr} in the formula:

$$\sigma_c=\rho \cdot c\sqrt{2 \cdot \epsilon_{cr}} \tag{1}$$

According to the results of complexly experimental studies of the unleavened ice in 1967-1969, based on the physical model of the Kheisin D.E. and on the results study of the actual paintings of fracture the ice, a model of impact of solid sphere to ice has developed. It known as “Hydrodynamic model (GDM) of Kurdumov-Kheisin" **[4][5]**. This model considers only the impact vessel on hit thick ice, not destructible bend **[6]**. Moving of the vessel in the contact area in this model mathematically described as a continuous the process of extrusion of fine layer of crushed ice out of zone between the ship and the array ice. Basic parameters of GDM were confirmed experimentally by resetting the spheres with spherical contact surface on the surface of the ice sheet. This model has gained recognition not only in Russia but also in the United States. Based it, authors have developed a unified scheme use ice loads on onboard construction for ice breakers **[7]**. Using the new methodology were designed and built vessels ice navigation-type well-known series of like “Vitas Bering” and others, as well as a series of icebreakers "Arctic", having no analogues in the world. This technique is used and at present. In this method the specific energy of "mechanical crushing ice" ϵ_{cr} used as the parameter of the strength of ice.

For to determining the sum and points of ice loads to the ship the diagram distribution of pressure from ice field on board of vessel in described methodology theoretically were accepted in the form of a smooth parabola. But actually pressure distribution on contact surface as smooth parabola hasn’t been confirmed experimentally non by authors of this methodology, as well as non studies by other scientists.

As far as we know, besides described here the GDM, other models fracture of ice for to determining ice load on the ship currently not used. But there are such models available and there are results of studies that can be used for adjusting or replacing the GDM Kurdumov-Kheisin. This models are associated with results of deeper experimental research of specific energy of mechanical destruction of ice. For example, by the author of this article has been developed the phenomenological model of elastic-brittle fracture of sea ice, described in his articles, both in Russian and in English **[8][9]**. This model can be an alternative to GDM Kurdumov-Kheisin. The basic idea of the model: the energy of the moving ice field that was spent for one cycle fracture of ice (work done by external forces) must be equal to the sum of the "internal" work required and sufficient for breaking the ice for a thickness of a layer of destruction.

The developed model is based on a certain sequence processes occurring on the surface of the destruction. Researchers calls such sequence "mechanism of breaking the ice”, similar to the mechanism of crushed of elastic-plastic body on the front wave of the explosion. Action this mechanism within one cycle of destruction the ice, as it is traditionally in the mechanics of destruction mathematically outlines by basic system of equations of continuum mechanics, in the form of conservation laws of physical quantities: conservation of mass, momentum and energy. From dependency analysis which discussed in the mathematical model and characterize the physical state of the ice in the process of quasi-dynamic loading, appears an important conclusion about exit by leap of elastic energy (that was saved inside the body), in the form of a breach of continuity of ice and also in the form by leap movement of surface rupture in space and time.

In the solving of model appears conclusion about, that the elastic potential of macro-volume of ice have the leap on surface of fracture. He describes the moment release from the macro-volume ice the (hidden) elastic energy, which was received from outside during the growth of external load. Elastic energy is converted into energy of new surfaces - cracks, which results in the destruction, i.e. separation of macro-volume into pieces. By analogy with the criterion of Griffiths for "ideal" crack, one of the classics of mechanics the fracture G.P. Cherepanov had formulated criterion of brittle fracture as: "a minimal number of elastic energy, release due to brittle fracture (per unit mass), are Constant for the material" **[10]**.

Thus, the use of conceptual mathematical model of brittle fracture of ice had yielded a theoretical justification for the existence of physical - energy criteria of ice failure ϵ_{cr}. This value integrally takes into account not only the strength of all components complex structure of the ice, and the strength of the link between the components, but also all of the kinetic processes taking place within the macro-volume on the micro level of ice. However, for the determination of ice load on the court or on man-made structures, we not necessary to consider and mathematically describe mechanical, hydrodynamic, thermodynamic and other processes that occur on the surface of the devastation. Out of all these theoretical research is important to us conclusion that specific energy mechanical breaking the ice is a new type of fracture criterion is without force factor – it is the energy criterion of strength.

3. Review of studies of specific energy breaking the ice

To determine the strength of ice to the punch, usually doing one of two types of experiment. The first type of tests are for individual samples of ice. In such experiments used headframe Pejeh or pendulum headframe Sharpie. On the headframe Sharpie get the impact strength (resistance) of fracture the ice a_k (kg/cm). On the headframe Pejeh is determined the work of destruction a_s (kg/cm^2). The second type of test on dynamic strength of ice - "the Drop Ball Test method" (DBT): tests by of the hard spheres, which free falling on the surface of the ice sheet. This method more accurately simulates the destruction of the array of ice when work icebreaker or under the impact of the ice sheet to the basic design of hydraulic structures, than the test results of the samples.

Initially the Drop method of Ball Test, similar to design method of Brinell, was applied for studies of the dynamic hardness ice H_B (j/m^2). The numerical value of this parameter, as it is known, is determined by dividing the value of the kinetic energy of a body hitting the $U_{cr} = MV^2/2$ on the value of the surface area of the imprint, formed on the surface of the material as a result of the introduction of a spherical Indenter- S_{cr}:

$$S_{cr} = \pi(\frac{D}{2})\left[D - \sqrt{D^2 + d_o^2}\right] \qquad (2)$$

Usually in the "classic version" of this test (DBT) in cases calculating the dynamic hardness ice H_B are measuring diameter d_0 of the imprint, but in cases calculating the specific energy of breaking the ice ϵ_{cr}, as well is measuring depth h_0 of imprint.

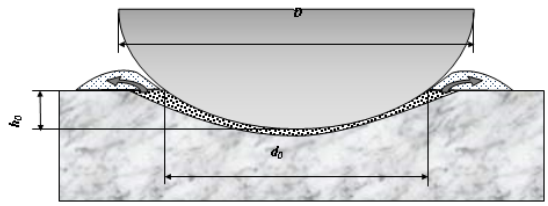

Figure 1: The usual scheme of measurement of parameters the imprint of the spherical indenter after its introduction into the surface of the ice sheet. Showing products fracture of ice, compressed into a solid mass and remaining under the surface of the cargo, as well as the crumb ice, which was extruded from the contact area.

Therefore, the precision the numerical value of the volume of destroyed ice is a determining factor in the computation of specific energy of its destruction.

To determine the “specific energy of breaking the ice” ϵ_{cr} a energy of the body U_{Cr}, which was spent on fracturing of the ice, refers to the volume of imprint W_{Cr}:

$$W_{Cr} = \frac{\pi}{6} h_0 (\frac{3}{4} d_0^2 + h_0^2), \qquad (3)$$

where: h_0 is calculated on the value of d_0 by using depth of imprint.

At begin time a Drop Ball Test was used by in 1952 year V. L. Tsurikov, and L. E. Veselova for defined Dynamic Hardness of ice of the northern Caspian Sea **[11]**. The influence of physical parameters of ice and its structure on value H_B by these scientists have not evaluated.

In 1965, the H. N. Dementiev **[12]** as an experimental apparatus for determination of dynamic hardness of ice used a special tools - drummer with spherical tip (drummer of type DorNII). In the same study, this scientist have received the first, famous for us, the numerical values of specific energy of mechanical destruction of sea ice ϵ_{cr}. For weakly saline sea ice H. N. Dementyev received ϵ_{cr} = 5 ÷ 30 kg/cm^3 = 0.05 ÷ 0.306 din/cm^3, and Antarctic sea ice ϵ_{cr} = 10.5 ÷ 33.8 kg/cm^3 = 0.11 ÷ 0.34 • 10^2 din/cm^3.

It should be noted that these and some other research values of H_B and ice ϵ_{cr} had exploratory, non system character. The results experiments of these authors did not find application in the engineering practice, because no theory has been developed using the energy characteristics of strength of ice nor in the calculation of ice load on structures, nor to calculate the strength of icebreaker.

But in the last 50 years by the method of Drop Ball Test, Russian researchers, experimental determination of the hardness and specific energy breaking the ice were conducted and for practical purposes.

The first special experiments of specific energy breaking the ice ϵ_{cr} for the practical application in calculations of load ice on board of ship were undertaken a team of researchers led by D. E. Kheisin in St.-Peterburg in 1969-69 years **[4][5]**. This research included cubic test on tensile strength of ice from sea and lake, a study the structures of shattered ice zone in its array in impact areas, data-bound all parameters to temperature of ice, his salinity and density. The steel body-indenters 150-300 kg weighing hemispheres were used in experiments.

The numerical values of specific energy breaking the ice ϵ_{cr}, obtained from the experiments, were used by authors to calculate loads on board the ice-breaker by injecting them into a new physical model **[6]**, which was developed for mathematically describe the process of the engagement ice sheet edge with the surface of the vessel.

In 1973-1978 in Vladivostok the group of scientists under the leadership by N. G. Khrapaty **[13]-[15]**, as analogy and as continuation of experiments group D. E. Kheisin from St.-Peterburg, were carried complex researches characteristics of strength the sea ice cover Amur Bay, but in this case, in addition to receiving basic physical and mechanical characteristics of sea ice, the main objectives of these experiments were:

- study the mechanism the fracture of ice, i.e. study the development processes of the elastic, brittle and plastic deformation of polycrystalline ice in the ground contact of solids with its surface;
- make the full factorial experiment to getting dependence the values ϵ_{cr} from factors: mass of solid indenters (spheres); velocity; radius of curvature of their surface, as well as temperature of the ice;
- study and getting the diagram of dependence of the magnitude ϵ_{cr} from temperature.

For the possibility to summarize and analyze the results to the measured groups of researchers from St. Petersburg, the far Eastern Group of researchers to conduct their experiments was taken part of solid indenters (spheres) with the same dimensions and masses. In this case also has been a full range of measurements of physical and mechanical properties of ice. To examine the destruction zone of ice in the impact point of the indenter, from the ice cover the blocks of ice were sawed and were produced thin transparent plates ice for measuring parameters of the zone of fracture of ice and for getting its photographs. The results of these experiments are the basis for study many aspects of the fracture of ice on contact with solid barriers, including this paper.

4. Analysis of the results of previous studies

From the above review of studies of the specific energy mechanical destruction of ice, you can make some conclusions. First of all, it should be noted that experiments. First of all, it should be noted that the early researchers the experiments to determine the specific energy mechanical destruction of sea ice ϵ_{cr} were conducted not systematically, and the results of such experiments have not been applied in engineering practice, because nobody of such researchers not offered the methodology of using the energetic characteristics of strength of ice nor in the calculation of ice load on the icebreaker, nor on the hydraulic installation basis.

In the last decades of the 20th century only two groups of researchers: in St. Petersburg and Vladivostok have conducted studies that were systemic in nature. In studies of these two groups of authors the value “specific energy mechanical fracture of ice " ϵ_{cr} was determined as the ratio of the steel hemispheres impact energy irreversibly expended to crushing mass of ice in volume of imprint W_{cr} (**Figure 1**). The amount of energy impact U_{cr} take equal potential energy raised the hemisphere taking into account amendments on numerical value of energy of the rebound. That amendment figured using the recovery factor, numerical value of which is found in each case experimentally.

These two groups of authors conducted their research not only to obtain information about ϵ_{cr}, as a characteristic of the "energetic strength of ice", but also for use this value in a specific applied targets for the calculation the ice load on the icebreaker, as well as the supports of hydro technical structures. For these purposes, by each from two groups of researchers were developed phenomenological models fracture of ice **[6][8][9]**.

As the themselves authors from a group of researchers from St. Petersburg, obtained in their investigations the numerical value of specific energy mechanical fracture of ice ϵ_{cr} are highly approximate because they failed to numerically assess the costs of impact energy on education "zone of the pre- destruction or pre- crushing"- i.e. energy for education many cracks in the ice, as well as on the large and small chipped of pieces of ice on its surface. The increase of heat energy in an array of ice upon impact from energy indenter and also the kinetic energy of the flying shards of ice not accounted. Researchers also failed to take into account the energy of elastic waves emitted in an array of ice upon impact from the indenter, and also the energy flexural vibrations of an ice cover. These researchers believed that on the crush the layer of ice spent a smaller fraction of the impact energy, but almost the entire volume of the impact energy is spent on squeezing and extrude the mass of products of crushing of ice from the contact area. They believed that the main process of destruction the ice plate is continuous process of squeezing the fine layer of crushed ice from the zone between the ship and the solid an array of ice.

But, along with the shortcomings of this group of researchers, experiments showed that specific energy ϵ_{cr} is fairly stable physical value. The numerical values deviation $\Delta\epsilon_{cr}$ from average values of each experience are normal law and practically do not exceed $\pm 2\sigma_s$. As demonstrated by the analysis of the results of these studies, the range of values ϵ_{cr} obtained experimentally is considerably smaller than for the mechanical characteristics such as durability natural ice on compression and bending, defined on the small specimens. But dependence values ϵ_{cr} from the temperature has not been established, therefore the practical use of the results of these experiments are very difficult.

Unlike the GDM model (extrudes products of ice from contact area) model the author describes a cyclical process of breaking the ice in his contact with the bow of icebreaker or with the surface of basis of ice-resistant platform **[9]**. One cycle of fracture of plate ice consists of three phases, each of which describes a differentially, taking into account the physical and mechanical processes of destruction of ice and movement of products of its destruction. But in our model, the main physical quantity, which determining the cost of energy on the fracture of ice, is the specific energy of his mechanical fracture ϵ_{cr}.

As a result of the experiments was found influence conditions of experiments on the physical value output: the specific energy of mechanical destruction of ice- ϵ_{cr} . The results of two full factorial experiments very clearly indicate that the magnitude ϵ_{cr} does not depend on the conditions of the test, namely: from body weight-Indenter, its velocity and radius of curvature of its surface (published in **[16]**).

But, at the same time, as a result of the experiments was found the dependence of magnitude ϵ_{cr} for sea ice from its temperature between 5ºc to in the interval, -0,5°C to −17°C. The relationship $\epsilon_{cr} = f(T^0 C)$ can see on **Figure 2**, it was found at firstly in our experiments.

To construct this curve were used more than 700 test points. On this diagram two the short straight lines the results of researches' of dependency the values ϵ_{cr} from the conditions of the experiments are showed. As can be seen from equations, which describing these short straight lines - such settings as the mass of a spherical body M , its radius R and the speed of collision V are absent in these equations, because they do not affect the output values in the experiment.

At the same time on the graph may clearly see, that points of values ϵ_{cr}, defined for by one particular value of temperature, have a big range of values. This is due to the fact that here we have the results of values ϵ_{cr}, obtained at a constant temperature of ice, but with varying impact energy - the kinetic energy of hemispherical steel cargo U_{cr}.

We have analyzed the results of the experiments, which were carried out by a single temperature. It turned out that really, the diagram of dependence $\epsilon_{cr} = \phi(U_{cr})$ when $T^0 C = const$ has an "undulating". If draw this graph in logarithmic coordinates, can clearly see, that there are characteristic maxima and minima of the value ϵ_{cr} (**Figure 3**).

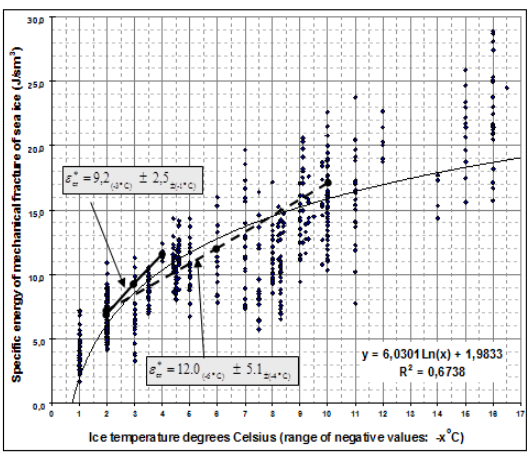

Figure 2: A curve of values of specific energy of mechanical fracture of sea ice, depending on the temperature.

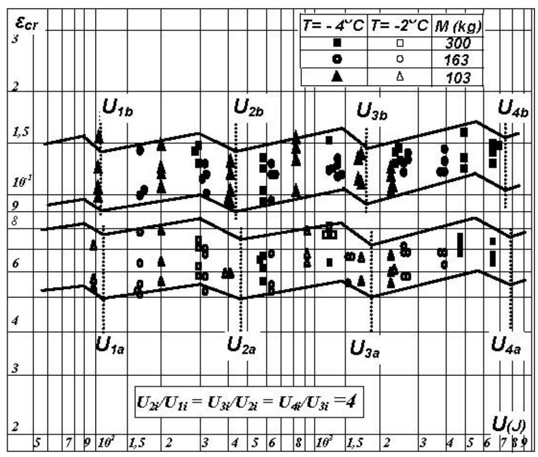

Figure 3: Graph of the depending of values of specific energy fracture of sea ice from the kinetic energy of the sphere.

But the periods the maximal and minimal the numerical value ϵ_{cr} on graphs $\epsilon_{cr} = \phi(U_{cr})$ say, that the destruction of the ice in the process of introduction of solid sphere occurs in several cycles. Each cycle of destruction − is the difficult process of the destruction of the ice layer, which occurs in three stages. Stages of fracture the ice in one cycle of introduction are detailed in our article **[9]**, which shows that in the first phase of destruction in each cycle, the accumulation the elastic energy (elastic deformations) implement as cracking this layer into blocks and crystals. After them, continuous crushing blocks and ice crumbs are occurs, products of fracture of ice are squeezing from the contact area in the second phase of fracture. The residues of an ice are crimping to the limit of ice density at the end of the cycle of destruction in the third stage. Depending on the energy sphere-Indenter in one blow could be implemented in a few cycles of destruction - that can be destroyed by multiple layers of ice. **Figure 4** shows a spherical array segment, on which a load from a rigid spherical indenter surface.

Such findings are in good agreement with the results of research of such experiments on the rocks **[17]**.

Authors of this experiments also have found, that when spherical indenter is embedding in an array of rocks, nature of destruction during one embed have a cyclical character. According to their experiments results with rocks, as well as the results of our experiments with ice, depending on the initial value of the kinetic energy of the indenter, the embedding process might stop at various stages of next cycle of destruction of an array of material.

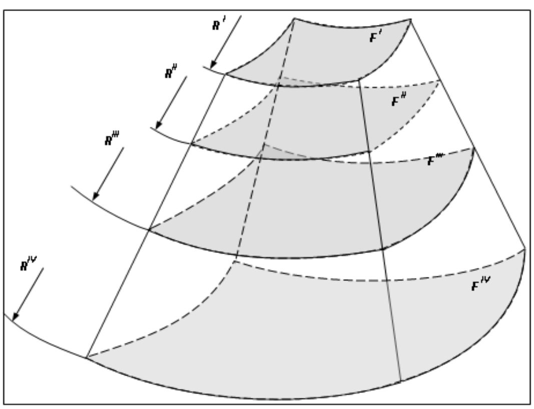

Figure 4: Spherical array segment of ice, which is undergoing a layer-by-layer destruction. The thickness of crushing layer $R_i - R_{i+1} = \Delta R_i$ can only be determined from experiment.

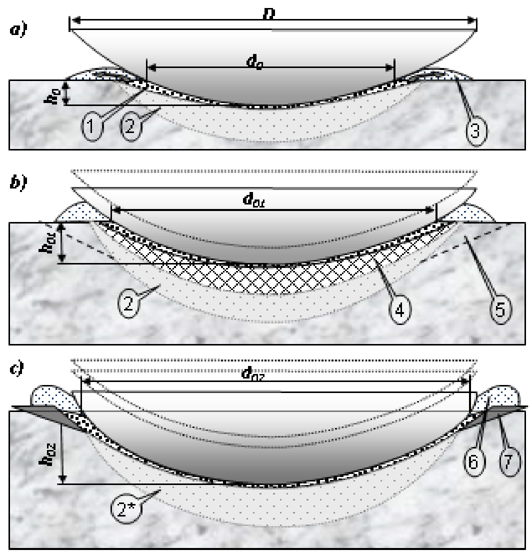

Figure 5: The separate fragments of the fracture process of an array ice under the spherical surface of solid body. 1- the pressed layer of products of fracture of ice, which was crushed in the previous cycle of destruction; 2 - the zone of elastic stress and strain; 3 - products of fracture of ice was squeezed from the contact area in the previous cycle of fracture; 4 - start of the cascade of fracturing of the ice in elastically compressed zone after accumulation the energy more as ϵ_{cr}; 5 − the sectors of ice, which getting lateral pressure from the products of fracture of ice, which are compress beneath the surface of the body and are extruding from the contact zone; 6 - extruded from the contact area products of fracture of ice in this cycle of destruction; 7 − splitting "triangular" pieces of ice on the circular caverns of destruction.

Given that the ϵ_{cr} is determined by the ratio of the initial energy of the Indenter to the volume of imprint, the graph $\epsilon_{cr} = \phi(U_{cr})$ has periodic nature for single value temperature of ice, but varying for the initial energy of the Indenter.

The minimum values of this magnitude have place in the case, if occur the complete usage of kinetic energy U_{cr} of the body on the destruction of whole a number of layers of rock (on **Figure 3** see: $U_{1i} \cdots U_{4i}$), and the maximum - is when under the Indenter surface remain products of fracture of ice don't extruding from the contact area that reduces the depth of the imprint and, accordingly, volume of.

Figure 5 shows the separate fragments of the fracture process of an array ice under the spherical surface of solid body.

In **Figure 5**a showed the start of a new cycle of breaking the ice. Energy of the solid body through a tough gasket of products of fracture of ice, which was crushed in the previous cycle of its destruction (position 1) passed to an array of ice, creating a field of elastic stresses and strains in the form of dense core (position 2).

In **Figure 5**b showed next position of the movement of the body down. Here, in compression zone (pos. 2), the stresses of elastic compress are transiting to the brittle fracture and the start of the cascade destruction of layer ice in this zone (pos. 4).

Ending this process coincides with the end of process extruding products of fracture of ice (pos. 6), whose lateral pressure produce popping (shear) triangular sections of ice (pos. 7) on the border of the contact. Mathematical description of the process of shear (chipping) ice on the border of contact with an array of ice is detailed doing in the work of the author **[18]**.

In **Figure 5**c showed the end of the cycle the fracture of ice, when the products fracture somebody layer of ice are pushed out from the contact area, their residues pressed under the surface of the body as a tough gasket. If to this point, the energy of the body is exhausted - it stopped and free relies on an array of ice, not creating a field of elastic stress analysis (pos. 2) underneath the ice. Therefore, in this case, the body does not get return (bounce) because the stock of elastic deformations in the array has not been created. Specific energy of destruction, calculated for the occasion will be the minimum value and you could argue that it most productively spent on fracture of ice. This value ϵ_{cr} can be used in calculations as effective. This hypothesis could be formulated as follows: the minimum value ϵ_{cr}, obtained from the experiment can be viewed as the energy constant for contact fracture of the sea ice at a given temperature.

However, if the body has still remained a stock kinetic energy that causes it to move forward, in the array of ice underneath is the elastic stresses and deformations (pos. 2). And if the body is not enough energy to fracture the next layer of ice − the elastic deformations of ice comeback part of the energy, not spread over in an array to body, who will receive the opposite movement up (bounce). In the calculation of the specific energy ϵ_{cr} the returned part of the energy we must to exclude from the calculation as "inefficient" spent.

The change of ϵ_{cr} can be determined theoretically depending on reserve of kinetic energy of body under condition of a constant ratio of radius body and the imprint depth of body for one cycle of fracture $D/2\Delta R_i = const$ (**Figure 4**). At implementation of this hypothesis the ratio of kinetic energy U_{i+1}/U_i will be constant. In author's tests for loads with diameter 0.56m and mass 300 and 163kg the indicated ratio was 4 (**Figure 3**). This ratio is correctly only to cases of "full" (without the return) energy expenditure of the Indenter to fracture the ice in one or more cycles. The coefficient of shock energy usage K_r, which was spent on the material failure in this case is maximum, if number of cycles (layers) of failure increase, coefficient tends to $K_r \to 1,0$. If next layer of material not completely crushed, according to the data of the experiments, at the expense of elastic energy, which was stored in an array from compression by indenter, a part of the energy returns to indenter, as a result of which indenter gets the inverse movement ("jump away") from an array of material.

The coefficient of shock energy usage K_r on material failure in this case is maximum and with ascending of cycle amount (layers) of failure it tends to $K_r \to 1,0$. Not crushed completely the next layer of material, according to the data of the experiments, at the expense of elastic energy, which was stored in an array from compression by indenter, returns to indenter a part of the energy, as a result of which indenter gets the inverse movement ("jump away") from an array of material.

The coefficient of shock energy usage K_r in our experiments were measured **[9]**. **Figure 6** provides a graph this coefficient, which depends of shock energy. This curve also has a recurring character and show, which part of the energy of the indenter was used for destruction of ice. It a graph also was found only in our experiments.

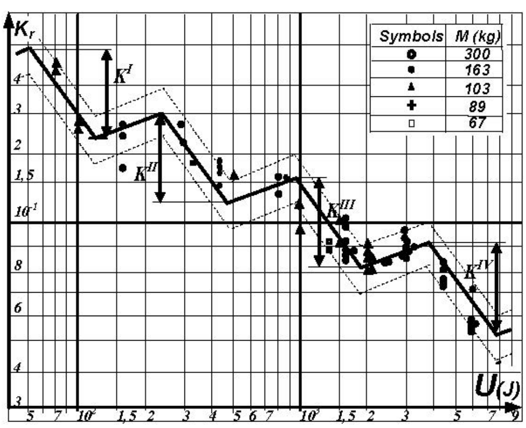

Figure 6: Schedule changes coefficient of usage of shock energy K_r which depends on the number of cycle's destruction of ice

5. Conclusions

1. The fracture of the array of ice by testing of method DBT occurs by cycles (layers), the number of cycles of fracture in one blow depends from initial velocity indenter;

2. In each cycle of fracture there are phase (process) cracking of ice to on blocks; crushing blocks in the icy crumb; extruding the crumb ice from the contact area; compressing remnants of crumbs to state of tough gasket and then - transfer of energy through tough gasket to the next, not fractured layer of ice;

3. Specific energy of mechanical destruction of ice ϵ_{cr} does not depend on the conditions of the test: body weight and speed (the initial energy loading), the radius of curvature of the surface of the Indenter is a function of only temperature ice − it is main parameters of his physical state;

4. The minimum specific energy mechanical fracture of sea ice are the constant its energy strength for each specific temperature within the range of its existence in nature;

5. Specific energy of mechanical fracture of ice ♏cr comprehensively describes the process of destruction of the macro-volume of sea ice when his contact with hard surfaces of ships and offshore structures, so this feature can be used in the calculation of the strength of such objects.

By analogy with the criterion of Griffiths for "ideal" crack in micro-volume, criterion of complexly fracture of the macro-volume of sea ice can formalize such formula: "a minimal number of kinetic energy, necessary for to release to fracture of sea ice field (per unit mass), are "Energetically Constant" for this material".

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