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DETERMINATION THE EFFECTIVE PART OF ENERGY INDENTER'S THAT SPENT ON FAILURE OF ICE

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ABSTRACT
Known Drop Ball Test method (DBT) allows to receive the dynamic hardness of ice and of specific failure energy. The experimental research has proved that a specific failure energy of ice can be used for the calculation of ice load on offshore structures and hull of icebreakers. The types and failure mechanism of ice, which are realized in the process of dynamic experiment with DBT method practically, correspond to types and mechanisms failure of the edge ice field in contact area of platform. The correct definition of part of the kinetic energy of the indenter which is lost only on the failure failure of ice block is important for power characteristic of sea ice. The paper presents the determination of effective part of the energy of the indenter consumed on the failure failure of the ice, taking into account the loss of energy indenter on ice cover vibrations and other losses.

INTRODUCTION
The first sentence of mathematical expression of ice pressure on the structure was second Newton's law. This experimental law explains how the mechanical motion of a material point changes under action of the external forces, but use of this law, according to many famous scientists-mechanics, not sufficiently justified for use in solving problems like this. Indeed, in an identity $\boldsymbol{F} = \boldsymbol{m \cdot a}$ the force should be independent and from body mass m, and from its acceleration a. But such specific independent properties was not described yet including Newton.
Achievement of failure mechanics currently widely known and the task of ice failure in front of the structure is seen as the task failure of ice block through the formation of shear and normal rupture cracks. Main crack that divide a body into parts can be formed as a result of long-term accumulation (rise) of stresses in the ice cover and also when these stresses reached its critical values as a result of rapid loading of ice block (according to Griffiths).
The same concept of the developing of crack when the tensile stresses in crack tip reached critical values was supported by other scientists. For example, Slepân L.I. (1990) in his work on modeling of ice failure said that "regardless of the type and level of volumetric damage to the structure of the body, the energy released from the elastic body is proportional to stress values and therefore it should be related to stress norming...". But here we don't see answers to many questions, including the main question: in what part of the design should be considered the tensions for comparing them to such a criterion of failure. The lack of answer to this question causes the consideration of other criteria of material strength based on the approaches alternative to force criteria.
In known work of Sih and Liebowitz (1975) it was shown that a number of researchers tried to establish the equivalence between force and power failure criteria in the development of the Griffith's theory. For example Sanders (1960) "... reformulated the two-dimensional Griffith's theory and got an equivalent the criterion, containing the integral on some counter covering the crack tip. His result is that the *failure energy criterion in principle is equivalent to the assertion about the critical value existence of the stress intensity factor*, beyond which starts the crack growth".

It is also known that the growth cracks dividing the body on parts leads to the release the accumulated elastic energy in the material, in the form of its redistribution to a surface energy of the newly formed surfaces as result of the body destructure. The classic approach of failure mechanics based on the nature of the phenomenon, has been proposed by Griffiths and has the form (Sih and Liebowitz, 1975)

$$-\frac{dU}{dS} = 2\gamma \qquad (1)$$

where $\boldsymbol{dU}$ is the total energy change of the system, part of which goes to creation of the new surface, which leads to a change of its area on the $\boldsymbol{dS}$. Here 2γ is perceived as the total work (per unit area dS) in the failure zone - the specific surface energy, necessary for the formation of a new surface in the body.

But there is another approach in the energy concept of failure which based on thermodynamic approach about of strength and failure of solids. E.g. Fedorov V.V. (1971) proposed the *Thermodynamic theory of strength and failure of a solid body*. Author invited to take as a criterion strength "… a level of accumulative internal energy *in deformable material* the critical value which ε_{cr} is not depend on the conditions of deformation and *is a physical constant of the material*".

This theory is based on thermodynamic nature of deformation and failure of solid bodies, which asserts that "until the moment of formation the critical size of crack and of final failure is preceded by a gradual accumulation in the deformable volume of material of internal energy. The failure comes at a time when *in the volumes of the material* that responsible for the failure, accumulate the critical value ε_{cr} which defined by of interatomic force connections".

Cherepanov (1974) describes in the monograph "Mechanics of brittle failure" a "g*eneral theory of explosion action*". His solution of the "equations of conservation" has shown that an *elastic potential of mass unit* on the surface of brittle failure gets the drop that equal to the value of "the energy dissipation on surface failure per unit mass (heat, the energy of residual microstresses; surface energy of cracks etc.)". The author claims that "this condition on analogy with the criterion of Griffiths can be formulated as: minimal amount of elastic energy, that released due to brittle failure (*and related to unit mass*), is a constant of the material. For definition this *constant,* similar to a physical sense of the magnitude to γ in the theory of cracks necessary make specially assigned experiments...". Further, in considering the process of the failure of the fragile body by interacting indenter, Cherepanov (1974) shows, that the criterion of failure of elastic block is a level of *specific energy* accumulated in it, necessary and sufficient for formation *in the unit of volume* of considering material the crack of normal rupture.

Each of the two authors of proposed theories of deformation and failure of the solid body of the *main task* their further development and implementation of practical calculations estimate the strength and durability of various materials under various conditions of loading of solid body considers the *task of experimental determination "of this constant which is analogical with physical sense to the magnitude of γ in the theory of cracks*" (Cherepanov, 1974).

In some recent works the "... use of Griffiths energy approach to dynamic failure is characterized by specific surface energy, but different from the same physical value that determined from the static tests" (Gorbushin and Petrov, 2014). They experimentally determined the existence of a limit energy on failure of the particles, which also confirms the existence of a limit speed of fragmentation. These authors say that when used in the strength analysis of energy strength criterias (γ or ε_{cr} of author), you need to have their values, *experimentally defined within the same range of loading speeds the material in which the material will work in structure*.

The most important condition for conducting such experiments to identify specific energy of material failure is "... thorough experimental studies of the energy balance of a solid body in the process of deformation and failure of specific materials, in various temperature-time conditions ... " (Fedorov, 1971). Specification of experiments should be directed on the calculation of specific energy of mechanical failure of ice from a consideration of the energy balance equation, with condition of control the values of all the other variables included in this equation.

Thus, as applied to the problem of definition of specific energy of mechanical failure of ice ε_{cr} by method of DBT by analogy with the Griffiths approach to determining the value of γ according to Eq. 1 should use Newton's second law, as the only fair application of this experimental law, because in this case it defines the braking force (slow down) the body ***F = m· (- (dv/dt)),*** that enters into contact with an obstacle. In a moment of time of body stopping the force of its effect on barrier reaches of maximum value because acceleration of braking has maximum a=-(dv/dt =|max|. This law can be written in form of energetical balance by multiplying the above equation by on displacement of body ***dx = dv·dt***. Given that ***a = - (dv/dt)*** one get

$$m\left(\frac{dv}{dt}\right)\cdot dx = mdv\left(\frac{dx}{dt}\right) = m\cdot dv\cdot v = \frac{mv^2}{2} = -\int_0^h F\cdot dx, \qquad (2)$$

and this means that the change in kinetic energy of the indenter in result his penetration into the ice on to depth of the cavern of its failure h from its starting value to zero, is equal the total work of strength, fractured of ice in the volume this imprint $W_{cr}(h)$. To solve the problem of experimental verification of the above concepts of theories of deformation and failure of ice, equation of energy balance (2) in the application of the full-scale experiment can be written as

$$\frac{mv^2}{2} = W_{cr}\cdot\rho\cdot\varepsilon_{cr}, \qquad (3)$$

where W_{cr} is is the volume imprint of indenter on ice sheet surface; ρ is ice density.

From this equation of energy balance the values of specific energy ε_{cr} fixing the values of all parameters in equation in the each experiment

$$\varepsilon_{cr} = \frac{mv^2}{2W_{cr}\cdot\rho} = \frac{mgH}{W_{cr}\cdot\rho}, \qquad (4)$$

where ***H*** is the height of free drop of indenter of mass ***m***.

HISTORICAL OVERVIEW

The experimental research on determining of numerical values of specific energy of mechanical failure of ice always carried out by method DBT and has participated such experimental research no much number of researchers. Historical overview of the development this direction of ice technology is set out in the work of the author (Tsuprik, 2013a), from which are made some conclusions. First of all, it should be noted that experiments to determine the specific energy 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 or in the calculation of ice load on the icebreaker, or on the shaft of hydraulic structure.

In the last decades of the 20th century only two groups of researchers: from St. Petersburg and Vladivostok have conducted studies that were systemic in nature. The direction of research was not only to obtain information about ε_{cr} , as a characteristic of the "energy strength of ice", but also have applied targets for the calculation the ice load on the icebreaker hull as well as the shafts of hydraulic structures. The phenomenological models of ice failure were developed (Kurdumov and Kheisin, 1976; Tsuprik, 1978, 2012).

Hydrodynamic Model of contact ice failure

The authors from St. Petersburg noted about approximate values of ε_{cr} because they could not evaluate the energy losses of creation of "zone of the prefailure" with amount of cracks and ice split fragments (Likhomanov and Kheisin 1971; Kurdumov and Kheisin, 1976). The heat and also the kinetic energy of the flying ice fragments were not accounted, and also the energy of elastic waves emitted in an f ice cover upon indenter impact, and also the energy flexural vibrations of an ice cover. They adopted that energy loss on formation of small fragments was small and main part of impact energy was spent on extrusion. They considered the failure process as extrusion of ice fragments from the zone between the ship and ice cover. *This model was called as Hydrodynamic Model (HDM).* It was found ε_{cr} is fairly stable physical value with deviation $\Delta\varepsilon_{cr}$ ***with*** normal law and not exceed $\pm 2\sigma_{\varepsilon}$. As demonstrated by the analysis of the results, the deflection of ε_{cr} is considerably smaller than for the mechanical characteristics such as ultimate compressive and bending strength, defined on the small specimens. But dependence of ε_{cr} from the temperature has not been established, therefore the practical use of the results are impossible.
Later a group of researchers in Krylov's Research Center (Appolonov et al., 1999) attempted to clarify the HDM used in Russia more than 30 years as methodology of ice load analysis on the Arctic ships and ice-breakers. They noted that "experimental research works for justification of the HDM (Likhomanov and Kheisin, 1971) did not include the direct measurement of the pressures in the contact area, so the basic relationship of this model (with parabolic distribution the contact pressure – *author*) was not directly verified by an experiment". At the same time they analyzed the experiments results of western researchers on ice failure during its interaction with a solid body by a DBT method (Timco and Frederking, 1990, 1993), penetration of medium-scale indenters (Frederking, Jordan and McCallum, 1990), as well as the results of full-scale ship testing in ice (Masterson and Frederking, 1993), which unambiguously identified a pronounced peak character in the ice pressures on the contact area. This conclusion contrary to theoretical presentation of authors HDM, where is the smooth epure of the contact pressure. Therefore Appolonov with coauthors suggested reviewing this model by introducing the empirical factor to determine the local ice load, also taking into account the results of the their experiments. The series of experiments with using a specially developed copra were conducted, free fall hard hemispheres of varying masses and different initial velocity collision with ice were applied (ARCDEV project). The analysis of the DBT results performed in the range of ARCDEV project has shown that the pressure epure in the area of sphere contact with the ice has a character peak. So it does not confirm the adequacy of the HDM data to real contact stresses.

Model of brittle failure and crushing the ice on contact with indenter (MBFC)

From a brief review of studies aimed at finding new strength criterion for the sea ice to the use of this criterion in the calculation of ice load on to engineering constructions, it can be concluded that as such a criterion must be considered the ε_{cr} . In theory, researchers showed the criterion as a parameter, which characterizes *the internal property of a material that is independent of the various external factors*. The researchers also concluded that the need to prove this properties of the criterion by experimental studies. This criterion is a key parameter of the model of ice brittle failure, described in the works of Fedorov (1971) and Cherepanov (1978). In development of these theories, author suggested use for practical purposes, developed by him *a model of brittle failure and crushing ice* (Tsuprik, 1978, 2012). In these works also were studied the logical basics of the criterion described above and were showed that it satisfies the requirements of *consistency completeness and independence*. This criterion is inferred from the mathematical description of natural phenomena – from the failure of the solid materials (block of natural material - ice). This criterion is *not contrary to the natural process release of elastic energy* of the body with the development of cracks, that divide it into parts. It *fully describes the process of failure* as integrated result of the accumulation and the merger the damages, pores and cracks in to a main crevasse that splitting an block of material on the parts. Thus, the considered criterion has the clear physical meaning, simple mathematical formula and can be obtained from simple experiments.

GENERAL STATEMENT THE RESEARCH TASK OF ε_{cr} AS ENERGY CRITERION OF ICE STRENGTH

But in order to prove that the above hypothesis, which takes into account the complex processes of failure at the surface of solid ice, necessary to carry out a number the experimental determination of this criterion. That is, a mathematical model that is describing the process of failure by using a new criterion should be verified. Experimental studies should be carried out in two directions: the method must be selected for the experimental determination of the investigated value; should be research the normal requirements to the results of experiments of this kind, which will confirm compliance the values ε_{cr} with the empirical criteria of scientific knowledge.

The choice of method experimental study

Firstly, all experiments must be conducted on a uniform methodology. If as the method of the experimental determination of the specific energy of mechanical failure of ice is recommended use the DBT method, will need doing the *validization* of this test. Here the *validization* of DBT test should be viewed as *reliability* – it is characteristic of test, reflecting his ability to give results that match the goal of measuring values of the analyzed criterion and justifies the adequacy of this criterion for basic task.

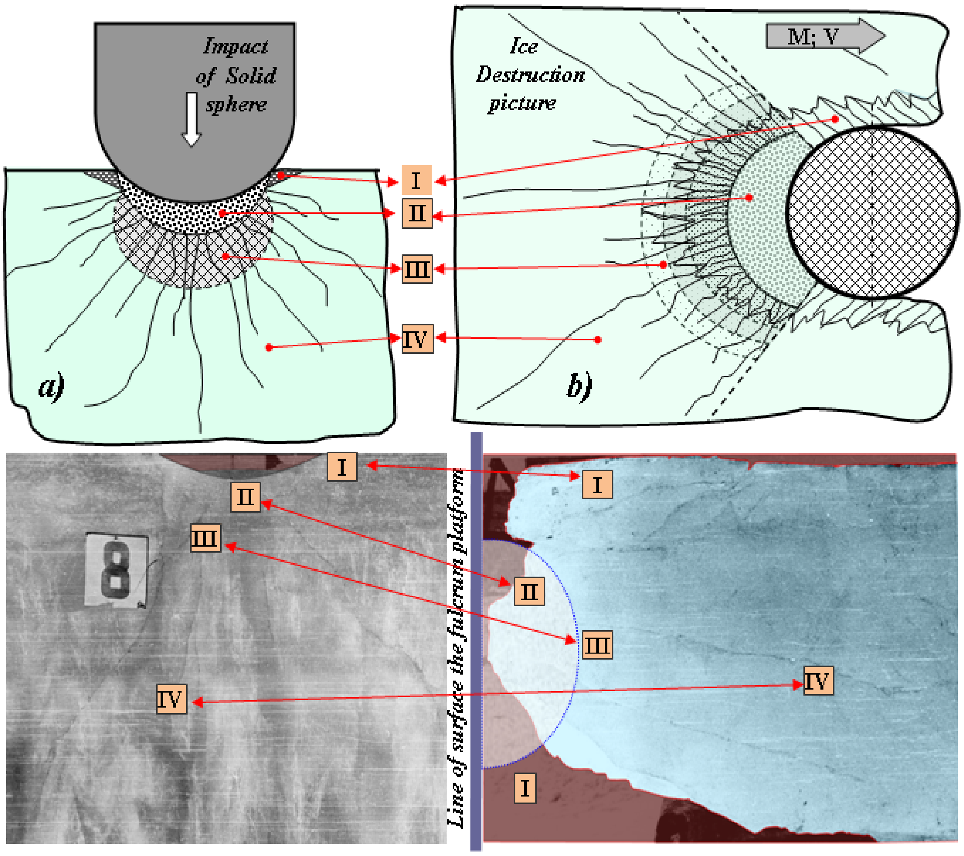

Figure 1. Comparison the crushing proces for ball drop and cylinder penetration into ice cover (tests of Khrapaty and Tsuprik, 1979)
I - splitting zone; II - zone of peak compressive failure;
III - zone of high cracking; IV - zone of main radial cracks

Secondly, it necessary ensure the adequacy (sufficiency) of the method DBT for the mechanism of the failure of ice, which was adopted in the mathematical model (in formula), which used for the calculation of ice load on the structure. This requirement can also be seen as a requirement of *conformity* and of *completeness* of the studied processes of failure – as coverage by of this characteristic of the whole complex of the modes of failure in such scale of the phenomenon, in which this parameter will be used for mathematical description of ice load on a structure;
Fig. 1 shows all a distinctive type of zones of the ice failure in the block, as caused by of steel sphere on the ice surface as well as by steel cylinder on the edge of natural ice. As can see from the photos, all the elements of the mechanism failure of ice are the same in both cases. This makes it possible to believe that the DBT adequately models the mechanism for breaking the ice in front of the cylindrical constructions of structure and can be applied to the study of the quantitative characteristics of strength, such as ε_{cr} .
Thirdly, it necessary to find all the physical factors that can affect the magnitude ε_{cr} and explore how each of them at this size, in other words, it is necessary to conduct full scale experiment.

Discussion of the requirements to the results of experiments on the verification of the model
Of the standard requirements for the results of experiments, that can confirm line of the values ε_{cr} to the empirical criteria of scientific knowledge are such criteria as *reproducibility, reliability* and *invariance*. Here the criterion of repeatability is regarded as stable repeatable result experiment running in identical conditions. Reliability as the reproducibility of the results of experiments, repeated in various conditions for the experimental determination of magnitude ε_{cr} is very important parameter, because the experiments can be conducted in different seas under different conditions. Verification of reproducibility and reliability of the method can be done by performing a large number of experiments, both in identical conditions, and different. For the method DBT, it is important to make sure that the radius and mass of the indenter do not affect the experiment values of specific energy of mechanical failure of ice ε_{cr} . If this condition is met, the method DBT for determining of values ε_{cr} can be considered *invariant*.

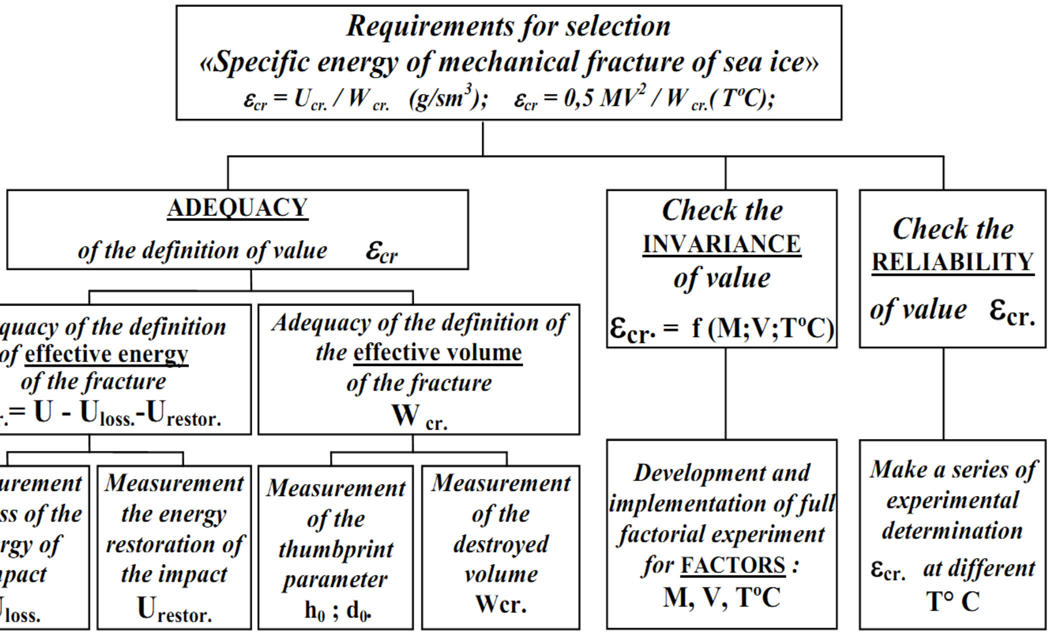

Figure 2. Flow-chart of the study some of the criteria compliance of experimental values of ε_{cr} its theoretical description in to the mathematical model of breaking the ice.

This conclusion can be obtained only through the full scale experiment, which will be take as the factors the mass of a spherical Indenter and its radius. Fig. 2 shows a block diagram of the DBT for exploring some criteria of compliance of the experimental values ε_{cr} her theoretical description in to mathematical model of failure of ice. As can be seen from the flowchart of research on Fig. 2 the most important experimental parameters, which determine the adequacy of the results of the experimental determination of magnitude ε_{cr}, are the effective volume of ice failure W_{cr}, the effective energy indenter $U_{cr.}$ consumed on ice failure. For the correct selection of methods determination of these parameters should be research as the mechanism failure the ice when formation the cavern under the surface of the Indenter as well as the distribution of kinetic energy of the indenter.

The results of research aimed at the theoretical and experimental study of the mechanism of formation of caverns in the ice cover under the surface of the Indenter with many cycles failure the ice for one act impact of sphere are given in the author's paper (Tsuprik, 2013c). Here in this work will be analyzed the distribution of kinetic energy of the Indenter to determine its effective part that is spent at the local failure of ice.

DETERMINATION OF "EFFECTIVE PART OF ENERGY" FOR ICE FAILURE

The result experimental research values of e ε_{cr} have significant scatter, because the investigations of many authors were done in the different natural conditions and with the help of different tools and devices. So the main task of the work presented here was research sizes of the energy losses distributed on to "secondary effects" which accompany the ice failure in to point of the impact of a steel sphere with the ice surface. These results very impotent for study of *the reproducibility, reliability* and *invariance* of magnitude ε_{cr}. If carefully consider the process of the impact of a steel sphere with the ice surface, can understand where kinetic energy U is spent. The kinetic energy of indenter U is distributed on to such parts (Fig. 3):

U_1 - on the developing of failure in the block of ice and on to bearing failure of the layer of crushed ice in the place of contact (imprint);

U_2 - on temperature rise and melting of icy crumb in the place of imprint;

U_3 - on to throw departure of the ice splinters on perimeter of imprint;

U_4 - on elastic wave distribution in an ice field and water;

U_5 - on to the bending of the ice sheet;

U_6 - on restoring of the velocity of reverse motion of indenter (due to elastically accumulated energy in an ice block).

Each of part full energy of a falling body has the specific value for definite conditions of impact, for instance, for such a parameter as the ice thickness, ice temperature and etc. On the basis of those considerations, "an efficient energy" falling body, spent on destroying the ice, will be determined by the formula

$$U_1 = U - U_2 - U_3 - U_4 - U_5 - U_6 \,, \qquad (4)$$

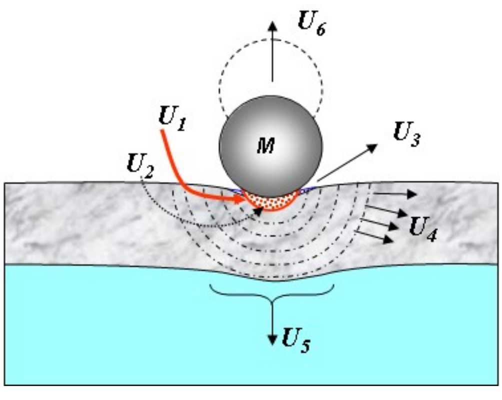

Figure 3. Distribution of energy of a falling body

Some of these parts of full energy are considered to be dominant in the volume of absorbed energy, while the others may be neglected due to their insignificance. For instance, firstly, loss energies $\boldsymbol{U_2}$ might be neglected because the ice temperature in nature differs from its melting temperature no more three a dozen degrees Celsius. Secondly, as tests showed, ice melts only a thin layer in the form of a film. This is explained by the ice low heat conductivity.

Energy value of $\boldsymbol{U}_3$ spent on to throw departure of the ice splinters on perimeter of imprint, possible to roughly determine as the equality of their the amount of movement to the momentum of the force that transferred to them:

$$mV_0 = P \cdot \Delta\, t,$$

where $\boldsymbol{mV_0}$ is the amount of movement of the mass of fragments; $\boldsymbol{P}$ ***is*** total force, reported fragments of time $\Delta\, \boldsymbol{t}$.

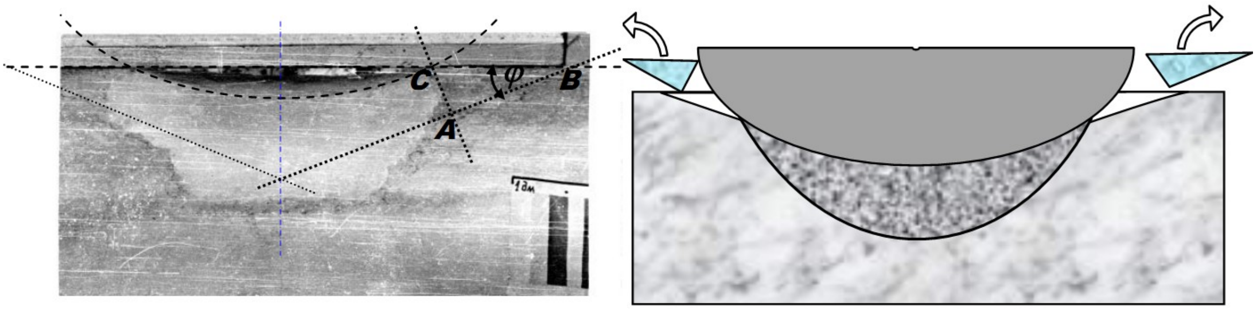

Figure 4. Kind of failure zone of ice below the surface of the spherical Indenter that penetrated in an ice block. Left and right on photo are visible angle beam cracks (AB), which would have to be chipped ice to free surface. Here shear angle is $\varphi = 25^o$.

In Figure 4 shows maximum amount of the ice splinters can be in volumes ABC. The majority part of the volume of ice failure will be fragmented continuously the interacting of body and will throw out in to the sides from imprint. Experiments on introduction of indenters of different shapes in different arrays of rocks show that when introducing the tool the angle of shear breed remains constant or changing to a limited extent (approximately from 22^0 to 35^0) regardless of the parameter embed tools, of stone fortress and the size of the zones of failure" (Kutuzov and Tokar, 1968). The authors explanation of the proposed permanence of shear rocks makes it possible to determine the quantitative difference between values of specific energy mechanical crushing ice that defined with use volume of the imprint and with use the true amount of the destroyed ice, taking into account the also amount of the breakaway ice.

From the picture you can roughly estimate the values of the AC in relation to the radius of the body and the size of the imprint. Given the angle $\boldsymbol{\varphi} = 25^0$, for the data of a particular experiment, in which a mass $\boldsymbol{M}$, velocity $\boldsymbol{V}$, the radius of the sphere $\boldsymbol{R_{sp}}$, the duration of the active part of the impact $\boldsymbol{t_{ia}}$ and maximum pressure on contact surface $\boldsymbol{p_{max}}$ were respectively the values $\boldsymbol{M}$ = 300 *kg*, $\boldsymbol{V} \approx 5$ m/s; $\boldsymbol{R_{sp}} = 0{,}28\ m$; $\boldsymbol{p_{max}} = 10^7 N/m^2$; $\boldsymbol{t_{i.a.}} = 0.05s$, you can calculate the momentum of force ejection of the shards out in to the sides from imprint. In view of the fact that the ejection of fragments will happen on the first quarter of the active phase of penetration, the pulse duration forces is: $\Delta\, \boldsymbol{t} \approx 0{,}25 \cdot 0{,}005 \approx 0{,}00125\ s;$ area $\mathbf{S_{AC}}$ about will be: $S_{AC} = 0{,}0053\ m^2$, and the impulse of the ejection of fragments is

$$P \,\Delta\, t = pS_{AC} \,\Delta\, t = 10^7 \cdot 0{,}0053 \cdot 0{,}00125 = 66\ N \cdot s.$$

The amount of movement of a mass of splinters, so much smaller than the number of steel sphere movements

$$\boldsymbol{mv} \ll \boldsymbol{MV}, \quad 66\, \boldsymbol{N\cdot s} \ll 1500\, N\cdot s$$

that is only about 0,5%. So the energy of the ejection of fragments of the $\boldsymbol{U_3}$ also can be ignored in the calculation of the energy consumption of the Indenter on to failure.

The energy spent on the distribution of elastic waves in the body and in the ice cover can be estimated by the formula (Goldsmith, 1965)

$$\boldsymbol{U}_{\boldsymbol{упр.в.}} = \frac{\boldsymbol{1}}{\boldsymbol{50}}\frac{\boldsymbol{V_0}}{\boldsymbol{C_0}},$$

where $\boldsymbol{V_0}$ is impact speed 1-6,5 m/s; $\boldsymbol{C_0}$ is speed of sound in the ice cover. For sea ice **C**=2500-3500 m/s.

So when such speeds of the body movement the energy of elastic waves in ice and in water, can be ignored because of the smallness of its values: U_4 = 1/25000 *U*.

Special theoretical and experimental investigations were held to find out the effect energy dispersion in ice block and bending of an ice sheet from acting the impact body. The amount of this energy depends on the thickness of the ice as follows (Krasilnikov, 1962)

$$U_{bend.} \sim \mathrm{H}^{\frac{-9}{5}}$$

This means that the increased ice thickness $\boldsymbol{H}$ sharply reduces the energy of fluctuations of the floating ice cover. Therefore, it is necessary to find thus ratio of the energy of the impacting body and the thickness of the ice sheet, which would not be instituting flexural waves and energy $\boldsymbol{U_{bend}}$. from of the overall balance of the impact energy can be deleted.

Exact solution of dynamic problems of the theory of elasticity for hitting on to the rods, beams or slabs, generally can't get because of the mathematical complexity of the dynamic equations of the theory of elasticity. Therefore, in addressing of engineering problems the impact are using a variety of approximate mathematical models of rods, beams and slabs. The results of the calculations task of the impact, that use such models are in most cases sufficient to accurately assess the main forces and kinematics characteristics of impact (Isaev, 2007).

This ratio can be obtained using the results of the calculations of body movement and characteristics of the plates listed Bagreev (1962) where is quite a common solution of similar problems for infinite plates in dimensionless quantities when have any dependency $\propto = \boldsymbol{kP^n}$.

From of work should, under certain ratios of the coefficient elastic foundation, velocity of body, cylindrical rigid of plate and the density her material, the impact force little depends from the mass of the indenter and to its value close analogy with the impact on the stationary barrier. This means that the ice cap at impact on it solid body, with a lot less its mass than the calculated according to the formulas in this article can be considered as a fixed barrier, and the energy spent on his bending is low.

As a result the ratios were deduced in the form of curves (Fig. 5) which show the relations between the ice thickness $\boldsymbol{h_i}$, its Young's modulus $\boldsymbol{E}$ and its "critical" mass $\boldsymbol{M}$. If body with lesser mass than those in the curves are used for given values $\boldsymbol{h_i}$ and $\boldsymbol{E}$ in tests, then the energy losses $\boldsymbol{U_5}$ may be neglected because the ice plate won't be bent. Theoretical estimations taking the water elastic reaction into account were experimentally approved. With this end in view in natural conditions measurements of the ice sheet bending were carried out with the help of seismometers and measurement devices for check flexural, associated with the bottom of the sea (Khrapaty, Tsuprik, 1976). The load mass ***M***, ice thickness $\boldsymbol{h_i}$ and ice temperature T°C were different in those measurements.

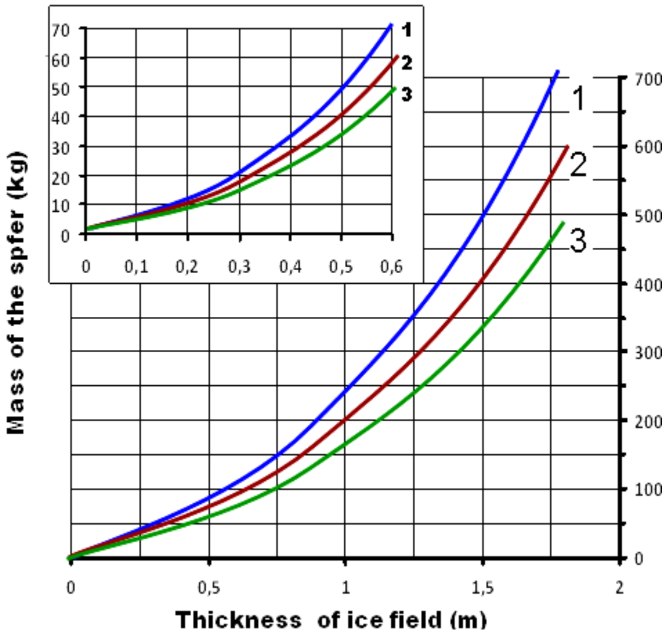

Figure 5. The curves which show the relations between the "critical" mass ***M*** of the body, ice thickness $\boldsymbol{h_i}$ for various values of Young's modulus ***E*** of the ice (1,2,3).

The energy portion of $\mathbf{U_6}$ may also be taken in ε_{cr} value calculation as neglected. This was done in experiments by introducing the concept of "energy losses" or "coefficient of velocity restoring". The energy restoring of hitting body is defined by the formula

$$U_6 = k \cdot U, \qquad k = 1 - V_{re}^2 / V_0^2 \,, \tag{5}$$

where ***k*** is the restoring coefficient of velocity after body impact; $\boldsymbol{V_0}$ and $\boldsymbol{V_{re}}$ are respectively: speed before the impact body and the speed of the rebound of the body.
This coefficient was found from the record the curve of the accelerometer, that was mounted on a falling body (Fig.6). That is why the energy portion $\boldsymbol{U_6}$ was subtracted from full energy ***U.***
Thus, one of the approximate estimates, it can be concluded that in the instant case, virtually all of the energy of impact will make the work of the failure of ice in the ground contact. Taking into account the results of available studies, This expression with the error of determining the "good energy" within 5% can be written as

$$U_1 = U - U_6 = U - U\,(1 - k); \qquad U_1 = k \cdot U, \tag{6}$$

Studies of specific energy of mechanical failure of ice ε_{cr} held in Vladivostok have confirmed the high reproducibility data's of experimental determination of this magnitude. On ice fields of Amur Bay was held two series of full scale experiments for studying of the functional dependency the values of the energy characteristics of ice strength from the mass of the indenter and its initial velocity introduction in to ice surface. The received quantitative data allowed to draw a clear conclusion about the independency of values ε_{cr} from the testing conditions, that is, from the mass and velocity of the steel spheres. Consequently of the values ε_{cr} received according to the technique proposed here, describe the ice energy criterion of strength truthfully and simply.

A dependence of the ε_{cr} from the temperature proved to be nonlinear that can see in relevant charts, previously published in several papers, where the data for a wide range of temperatures are shown (Khrapaty, Tsuprik, 1976; Tsuprik, 2013a).

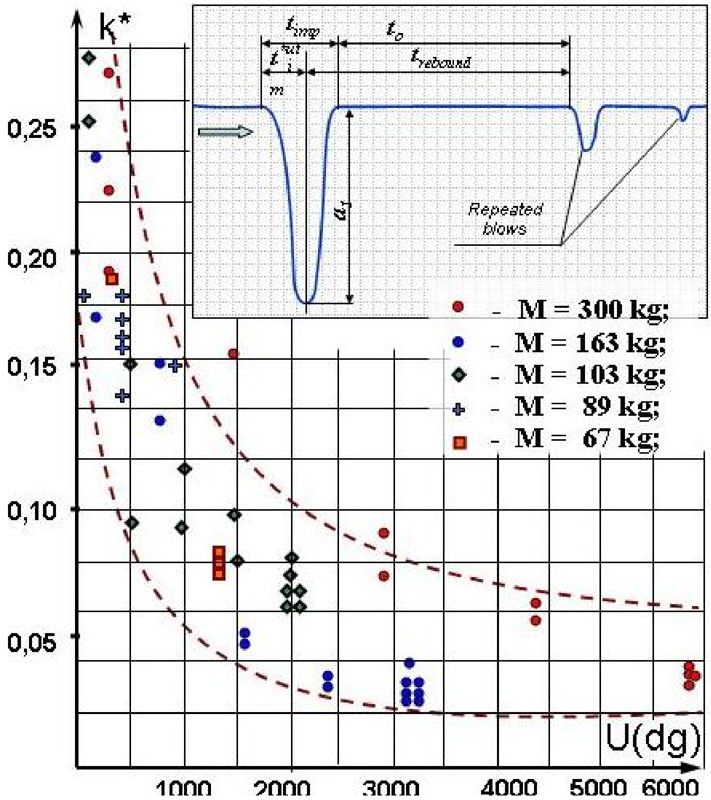

Figure 6. The record of the curve of the accelerometer and experimental data for the restoring coefficient of impact energy.

CONCLUSIONS

The ice strength parameter according to regulations is an uniaxial compressive test of samples is proposed to replace by strength parameter ε_{cr}. It seems to be reasonable for applying to calculation of ice force on offshore structures. The reasonability of is proved by the following statements:

1. The procedure of experimental determination of specific energy of ice mechanical failure is proved theoretically and by full-factor experiments.
2. The investigations carried out to establish qualitative parameters of a new ice characteristic meet the main requirements in the best way, which are usually necessary for such criteria.
3. The ice strength condition has a definite physical meaning, the strength indicator can be defined from the simplest experiments.
4. The procedure of obtaining initial strength parameter is simpler, more available and economic in comparison with the procedure of obtaining values of the ice strength ranges while testing its cubics for uniaxial compression. This provides actuality of this research and its further investigations in this direction.

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