

FRACTURE AND ITS ROLE IN DETERMINING ICE FORCES ON OFFSHORE STRUCTURES

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ABSTRACT

One of the most conspicuous phenomena in the Arctic is the fracture of sea ice. It is scarcely possible to travel far without seeing a variety of fracture forms, produced both by natural processes and by human activity.

At strain-rates below about 10^{-4} s^{-1} , deformation is dominated by creep, but at higher strain-rates fracture is much more important. One of the reasons for this is the very low fracture toughness of ice. The movements of ice in contact with offshore structures often induce strain-rates well beyond the level at which fracture begins, and so offshore structures will often operate in the fracture regime, and it is fracture processes which will determine the design loads. We consider the different modes of repeated fracture that will occur, and classify them into distinct mechanisms of crushing, spalling, and radial and circumferential cracking. Experimental and field observations are plotted on a deformation mode map. A theoretical treatment of radial cracking confirms that very low loads can propagate cracks to long distances; these loads are small by comparison with those calculated from theoretical models that treat ice as a plastically-deforming continuum.

1. INTRODUCTION

An engineer who studies the research literature on ice forces finds analyses dominated by theoretical models which treat ice as a material that deforms continuously. Most of the models apply plasticity theory (generally concerned with a material which

can deform indefinitely at a certain stress level), and some are based on creep and elasticity.

An observer in the Arctic sees a picture which is qualitatively different. Everywhere he looks, he sees broken ice, sometimes from horizon to horizon. The broken fragments are separated by cracks, and superficially at least they appear to have deformed relatively little, though there may be signs of continuous deformation by creep and flexural buckling, particularly in highly-stressed areas. This observation suggests that any complete analysis of ice forces on offshore structures has to take account of discontinuous fracture phenomena.

It is hardly surprising that fracture should be important. Common experience tells us that ice breaks easily, and measurements show it to have a fracture toughness of the order of $115 \text{ kN m}^{-3/2}$ (Goodman 1980), which is less than that of glass and one-thousandth that of structural steel. This fact is reflected in measurements of stress-strain-time relations. Figure 1, based on unpublished work by Ashby and Cooksley, shows schematically the relationship between minimum strain-rate and stress for pure ice in uniaxial tension and compression at -10°C . At low strain-rates, ice creeps continuously, and strain-rate and stress are related by a power law (Glen's law), and behaviour in tension and compression is almost identical. At strain-rates above 10^{-5} s^{-1} in tension and 10^{-4} s^{-1} in compression, fracture processes take over and become much more important than creep, though creep may still be significant at a microstructural level. In tension, fracture occurs at a stress between 1 and 2 MN m^{-2} , depending on grain

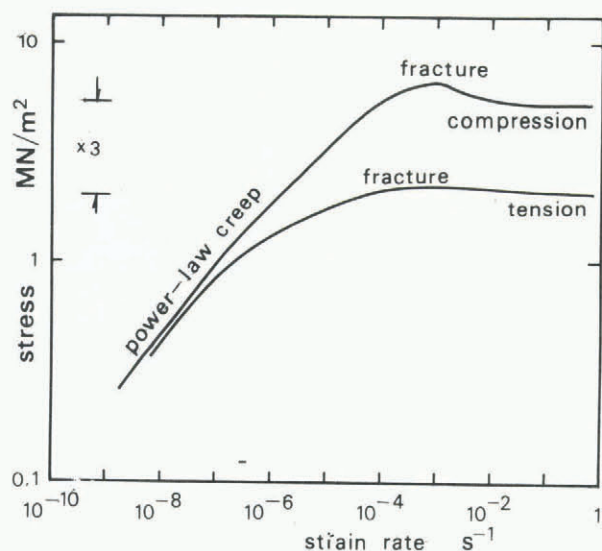


Fig.1. Relation between minimum strain-rate and stress for pure ice in uniaxial compression and tension at -10°C.

size. This is probably due to the unstable propagation of pre-existing microcracks or of cracks nucleated by creep deformation, on the same scale as the grain size. In compression, microcracks probably do not begin to propagate until a higher stress level is reached, and fracture follows the linking up of these distributed microcracks. A difference between tensile and compressive strengths is characteristic of brittle materials, though a factor of three between them is much smaller than in concrete and rocks.

The central role of fracture is confirmed by comparison of a number of situations in which ice deforms. They are listed in Table I. Each is identified by creep (in which deformation is continuous and the ice does not break up) or by fracture (in which markedly discontinuous deformation breaks the ice into distinct fragments). The classification is based on a broad macroscopic interpretation, and it has to be kept in mind that what appears as fracture on a large scale may also include intense creep deformation at crack tips. Each deformation has a characteristic velocity U and length L (defined as the distance over which the relative velocity is U); U/L has the dimensions of strain-rate if the deformation is continuous.

The comparison in Table I shows that creep dominates in slow natural processes, and fracture dominates when velocities are higher. It is consistent with the stress strain-rate relation, where fracture takes over from creep when strain-rates exceed 10^{-4} s^{-1} .

An offshore structure could have a diameter of at least 100 m, perhaps much more. The velocity of drifting ice is in the range 0 to 1 m s^{-1} . It follows that the velocity/diameter ratio ranges from 0 to 10^{-2} s^{-1} . If this is the ratio that determines the deformation mode, and if the critical value is 10^{-4} s^{-1} (which is of the right order of magnitude for a situation dominated by compression but without strong triaxial constraint), then creep will be the dominant mechanism if the velocity is less than 10^{-2} m s^{-1} (1 km d^{-1}), and fracture will be the dominant mechanism if the velocity is greater than that. However, observations indicate that the transition to fracture-dominated mechanisms occurs at a much smaller ice velocity: this may be because the length scale should be the ice thickness, or the characteristic length for a floating ice cover, rather than the structure diameter.

2. DEFORMATION MODES

The word "fracture" covers more than one kind of behaviour. Many authors have classified their observations of fracture in different ways (e.g. Schwarz and Hirayama 1973, Croasdale 1975, Kry 1982). Figure 2 illustrates one tentative classification of fracture modes close to the contact between ice and a structure. *Crushing* fracture (Fig.2(a)) involves the growth of cracks in different directions, with no obvious preferred orientation, through a zone whose dimensions are of the same order as the contact breadth and less than the ice thickness. The fragments are relatively small, and their length, width and thickness are of the same order. *Indentation spalling* (Fig.2(b)) occurs when horizontal cracks run roughly parallel to the plane of the ice, until they run out on the upper or lower surface. The spall fragments are semicircular: their thickness is less than that of the ice, and their radius much larger. *Radial cracking* (Fig.2(c)) is the growth of vertical cracks, directed radially from the contact region and running through the whole thickness. In a large ice cover radial cracks alone do not separate the ice into fragments, but they are often accompanied by *circumferential cracks* (Fig.2(d)) so that the fragments are triangular and trapezoidal. Modes are often mixed; in particular, it often happens that the contact region undergoes local crushing while radial cracks develop further away.

All four modes are observed in the field and in the laboratory, but the facts that decide which of them will occur are not fully understood. When a uniform ice cover moves against a cylindrical structure, the principal governing factors are the ice velocity U , the structure diameter D , the ice thickness t , and the breadth L of the contact between the structure and the ice (D and L are defined in Figure 2). Ice material properties such as temperature,

TABLE I. DEFORMATION MODES

	Velocity $U \text{ (m s}^{-1}\text{)}$	Length $L \text{ (m)}$	U/L s^{-1}	Mode of deformation
Antarctic ice cap	3×10^{-8}	10^3 (depth)	3×10^{-11}	creep
Alpine valley glacier	3×10^{-7}	10^2 (depth)	3×10^{-9}	creep
surging glacier	3×10^{-6}	10^2 (depth)	3×10^{-8}	fracture/creep
iceberg calving	10^{-3}	10^2 (thickness)	10^{-5}	creep/fracture
laboratory compression test	10^{-5}	10^{-1} (length)	10^{-4}	creep/fracture
laboratory indentation test	10^{-5}	10^{-3} (indenter radius)	10^{-2}	creep/fracture
Arctic gravel production island	1	10^2 (diameter)	10^{-2}	
rubble field	1	10^2 (width)	10^{-2}	fracture
icebreaker	2	20 (beam)	10^{-1}	fracture/bending
monopod offshore structure	2	20 (diameter)	10^{-1}	
bridge pier	2	2 (diameter)	1	fracture
ice ditcher	1	10^{-3} (cut)	10^3	fracture

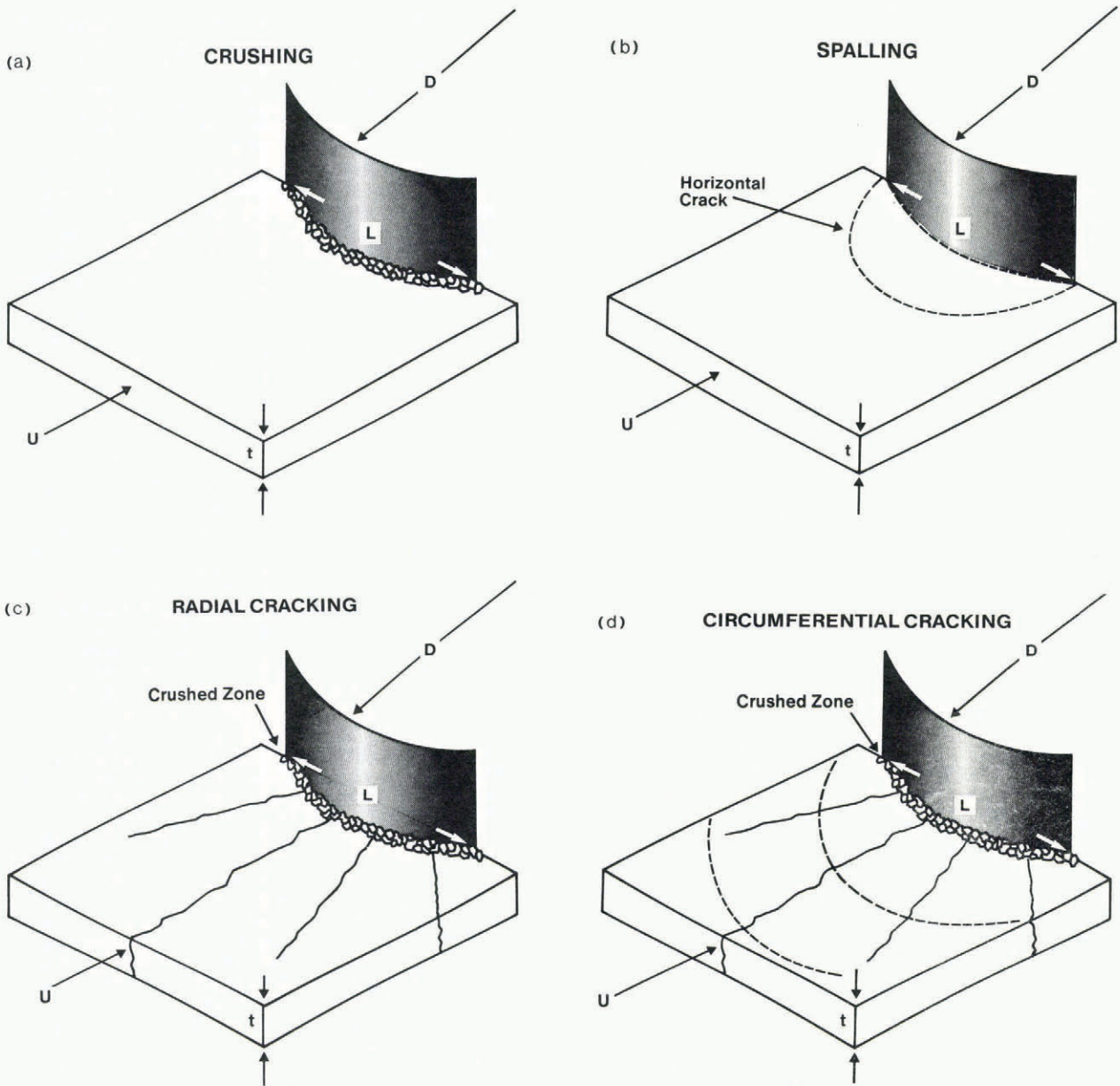


Fig.2(a), (b), (c), (d). Fracture modes.

salinity, grain size, grain orientation, and through thickness variations are also important. It is conjectured that the mode of deformation depends on the ratios U/D and L/t . U/D is the deformation rate identified earlier, and L/t determines the type of stress field that can exist close to the contact, since small L/t corresponds to plane strain and large L/t to plane stress.

Figure 3(a) plots observations of deformation modes on a diagram with axes U/D and L/t (with logarithmic scales). Many of the data come from tests with flat indenters, when L and D are equal. Although the data are not entirely consistent, a pattern does emerge. Figure 3(b) is a tentative deformation mode map intended ultimately to be used in the same way as diagrams delineating the regimes of applicability of different wave theories (Sarpkaya and Isaacson 1981), or regime maps in two-phase flow theory. It needs to be emphasized that this map is highly tentative and that it is based on limited data from observations on a small scale. It needs to be completed and corrected

as observations on fullscale offshore structures and artificial islands become available.

3. FRACTURE ANALYSIS

A long-term objective is to find a reliable way of predicting ice forces on structures needed for offshore petroleum production. The design maximum force on a structure will sometimes be limited by the maximum driving forces exerted on the ice by the environment (Croasdale and Marcellus 1982), but more often it will be limited by the strength of the ice itself. The maximum load must therefore depend on the deformation mode. One might compare the degree of variability between modes with that seen in civil engineering fluid mechanics, where flow is sometimes laminar, sometimes turbulent, sometimes dominated by waves, cavities and wakes, and sometimes influenced by multiphase phenomena such as cavitation and sediment transport.

Models based on plasticity theory have been widely applied (Ralston 1978), but are open to critic-

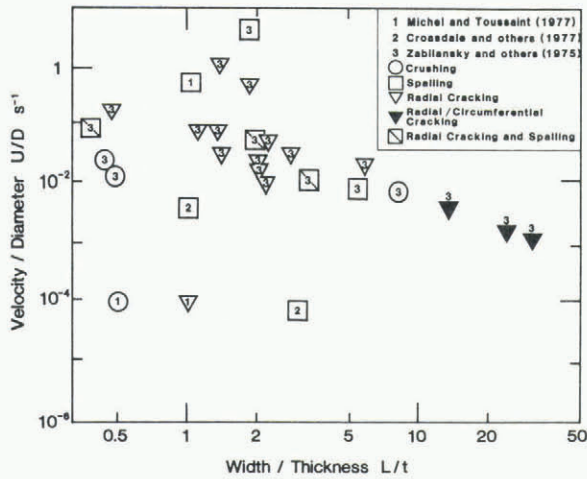


Fig.3(a). Observations of fracture modes as a function of U/D (ice velocity/structure diameter) and L/t (contact width/ice thickness).

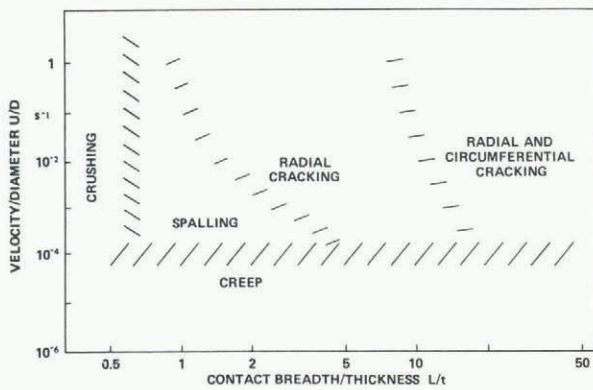


Fig.3(b). Deformation mode map.

ism as inadequate models of ice. The creep regime is discussed in another paper (Ponter and others in preparation*) using a method developed for the analysis of creep deformation in complex stress states. In the fracture regime, complete theories of all the different modes are not yet available. Here we outline a simple theory of radial cracking, intended to lead towards more refined theories and to generate order-of-magnitude estimates of cracking forces. Indentation spalling is discussed elsewhere (Evans and others in preparation [no title available]).

Fracture can begin at extremely low force levels. Imagine a uniform ice cover with a plane vertical side moving into contact with a fixed rigid circular cylindrical structure, fast enough for the ice to respond elastically to stress. The maximum contact pressure p_m is related to the force P between the structure and the ice cover by Hertzian contact theory, and is

$$p_m = \left[\frac{2PE}{\pi D t (1-\nu^2)} \right]^{1/2} \quad (1)$$

where D is the structure diameter, t the ice thickness, E Young's modulus, and ν Poisson's ratio. The contact breadth is $2Dp_m/E$, and so conditions close to

*Ponter A R S, Palmer A C, Goodman D J, Ashby M F, Evans A G, Hutchinson J W. The force exerted by a moving ice sheet on an offshore structure: I. The creep mode.

the contact generally correspond to plane strain through most of the thickness; in plane stress, the factor $1-\nu^2$ is absent. In the contact region, the principal stresses close to the upper and lower surfaces of the ice cover will be p_m (in a roughly radial principal direction), of the order of p_m (circumferentially) and close to zero (vertically) (Frederking and Gold 1972). It follows that if the ice crushes in uniaxial compression at a stress σ_c crushing can be expected when $p_m \sim \sigma_c$, that is, when

$$P \sim \frac{1}{2} \pi (1-\nu^2) \frac{Dt\sigma_c^2}{E} \quad (2)$$

If D is 10 m, t 2 m, σ_c 5 MN m⁻², E 10 GN m⁻², and ν 0.3 (appropriate values for ice), the corresponding value of P is only 70 kN. This is an estimate of the ice force at which fracture starts; the corresponding contact breadth is only 0.1 m, and so the ice has hardly come into contact with the structure. Continued movement of the ice towards the structure will generate a crushed contact zone (Fig.4(a)) within which the stress components are of the order of σ_c . This zone will extend progressively horizontally, as well as vertically inwards from the upper and lower free surfaces towards the midplane of the ice cover, where triaxial constraint tends to suppress fracture. The distribution of normal stress σ_{yy} across the plane of symmetry is shown in Figure 4(b); this stress component will be compressive close to the contact and tensile further away. If the maximum tensile value of σ_{yy} just outside the crushed region reaches the fracture stress in tension, a crack can initiate and propagate in the positive x -direction. Figure 4(b) shows such a crack extended to a length c . Its growth can be analysed through the methods of fracture mechanics, whose application to ice has been discussed by Goetze (unpublished), Smith (1978), Goodman (1979), and others. The crack can be idealized as an edge crack in a semi-infinite plate, wedged open by opposed crack-opening forces F (Fig.4(b)) equal to the transverse compressive force in the crushed region close to the contact. The corresponding stress intensity factor is $2.590 F/t\sqrt{\pi c}$ (Sih 1973). F should be proportional to the ice force P ; therefore, we choose to take F as αP , where α is a proportionality constant. Once initiated, the crack will extend until the stress intensity factor for the crack tip falls to the fracture toughness K_{IC} , i.e. until

$$K_{IC} = 2.590 F/t\sqrt{\pi c} \quad (3)$$

and so

$$c = 2.13 \left[\frac{\alpha P}{tK_{IC}} \right]^2 \quad (4)$$

Taking K_{IC} as 115 kN m^{-3/2} (Goodman 1979), α as 0.5, and t as 2 m, sample load values to propagate a crack are:

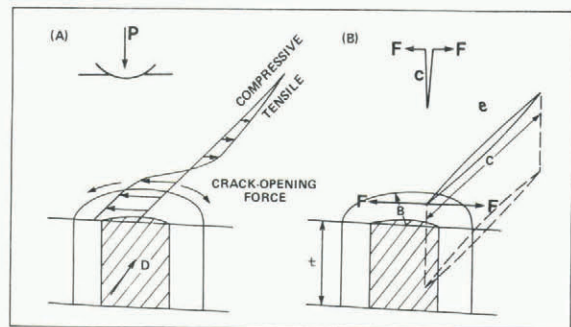


Fig.4. Distribution of stress in front of a cylindrical indenter (A), and a single radial crack opened by a wedge opening force F (B).

Load	Crack length
100 kN	0.1 m
1 MN	10.0 m
10 MN	1000.0 m

The growth of the crack is stable, but it extends very rapidly as P increases, and this result ought not to be sensitive to the details of the stress-strain relation, since the crack is advancing into the elastic region far from the contact, where stresses are low. The choice of α as 0.5 is comparable with the value found for axisymmetric indentation (Lawn and others 1980).

Stable growth of a radial crack at right angles to the edge of the ice cover does not itself lead to other kinds of fracture, but the process of initiation and growth of radial cracks can be repeated. In each of the right-angled sectors into which the crack divides the ice cover, there will again be a transverse tensile stress across planes that bisect the sectors, although the loading on a sector is no longer symmetric. A second and a third crack can initiate in each sector, the sectors can split again, and so on.

Analogy with axisymmetric indentation suggests that the array of radial cracks would have crack lengths comparable to the length of a single radial crack, except at very high crack densities, where the lengths of individual cracks would diminish.

The ice cover has so far been treated as if it were stress-free. It is quite possible for a stress to exist in the y -direction in the plate; if the stress is tensile, the growth of the crack can become unstable. Consider again the case of the single crack shown in Figure 4(b), if a remote stress σ_s exists in the ice, the stress intensity factor becomes

$$K_I = 2.590 \alpha P / t \sqrt{\pi c} + 1.12 \sigma_s \sqrt{\pi c} \quad (5)$$

If K_I reaches the critical value K_{IC} , the crack will grow to a length which is smaller than the roots of

$$0 = (1.12 \sigma_s \sqrt{\pi}) c \sqrt{\pi} - K_{IC} \sqrt{c} + 1.461 \alpha P / t. \quad (6)$$

The crack becomes unstable when

$$P = 0.086 K_{IC}^2 t / \alpha \sigma_s \quad (7)$$

and

$$c = 0.071 (K_{IC} / \sigma_s)^2. \quad (8)$$

When P and c reach these values the ice will split across. If the tensile transverse stress is 0.01 MN m^{-2} (less than 1% of the stress at which tensile fracture occurs, and of the same order as the stresses induced in floating ice by waves (Goodman and others 1980)), K_{IC} is $115 \text{ kN m}^{-3/2}$, α 0.5, and t 2 m, the critical force at which the sheet splits is 0.5 MN and the critical length is only 10 m. Thus very small tensile stresses will substantially reduce the force needed to fracture an ice cover. Transverse compressive stresses will, on the other hand, exert a stabilizing effect.

The estimates of P and c are not numerically precise, because of the need to estimate α , and ought to be checked by comparison with experiments on well-characterized brittle materials not subject to creep, following the parallel work on normal indentation by Lawn and others (1980). However the observations do confirm the observation that because ice has such a low fracture toughness, small forces can make cracks propagate a long way.

4. IMPLICATIONS FOR FORCE CALCULATIONS ON REAL STRUCTURES

The analysis above calculates the wedge opening force P required to propagate a crack radially away

from the structure. Because the ice must still clear around the structure, this load will not necessarily be the maximum load the structure will see. However it is instructive to compare the order of magnitude of P , with the total loads acting on a structure estimated from alternative models.

Consider first a plasticity model (Ralston 1978) for a structure which has a diameter of 100 m and ice cover which is 2 m thick. If the ice is idealized as a perfect plastic von Mises material with yield strength 5 MN m^{-2} (corresponding to an ice velocity of 0.02 m s^{-1}), and the indentation factor is taken as 1, Ralston's model would estimate the force on the structure to be 1000 MN (100 000 tonnes). This is 14 000 times the estimated force at which fracture begins and 100 times the force that can propagate a crack to a distance of 1 km. If the yield strength is 0.5 MN m^{-2} , the force calculated from a plasticity model would be 100 MN. More sophisticated plasticity models take account of anisotropy, and of yield functions that include the effect of the first stress invariant, but give results of the same order of magnitude.

Radial cracking may not itself limit the maximum ice force, but the gross changes of geometry that it causes must be taken into account in the load calculation. The presence of radial cracks may for instance allow flexural buckling to occur at a lower load than would occur in an uncracked sheet (Kerr 1978). Circumferential cracking will follow radial cracking, and it may limit the load because triangular fragments will break away and ride up over the uncracked sheet.

5. CONCLUSIONS

It is no more likely that there should be a universal ice-force formula than that there should be a universal formula for the force on a body in a moving fluid, and in the present state of knowledge, it would be unwise to expect too much.

Calculations based on elementary fracture mechanics confirm observations that suggest that many modes of ice deformation are governed by fracture. The corresponding forces are very small by comparison with forces calculated from plasticity or creep models, and this suggests that for certain geometries and ranges of movement rates fracture phenomena may determine design loads for offshore structures in ice.

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