1 Introduction

1.1 Initial Comments: Elasticity and Dissipation

Ice is present in many offshore locations where engineering activities are required. These activities include transportation and movement of materials related to human habitation, as well as resource development and use. The facilities for these activities require consideration of ice loadings and associated design. Transportation involves design of ice-strengthened vessels and icebreakers. Ice is a complex material, existing on earth at temperatures near its melting point. It is prone to creep under stress and to fracture. Yet it can produce extremely high local stresses on icebreaking vessels and structures, and ice can interact with fixed structures causing significant vibrations, with energy flowing into and out of the structure. The focus in the present work is interaction of structures with thick ice features and icebergs.

The stretching of a spring which returns to its original position after release of the stretching force embodies the idea of elasticity. In contrast to the elastic storing of energy, most mechanical processes involve dissipation and the creation of heat. The dissipation can occur internally, within the material, for instance the glide motion of dislocations in materials such as steel and ice, thereby generating heat, a process of internal friction. Dissipation can arise also from changes to the microstructure of the material being considered. Ice is a case in point, with large changes to crystal size involving dynamic recrystallization under high confinement and shear. The consequent changes to mechanical response are extreme and offer explanations for failure processes. We aim at a fundamental approach to mechanics of materials, in particular time-dependency, which accounts for such factors. The ideas of storage and dissipation of energy in mechanics can be represented by springs and dashpots, respectively (Figure 1.1), and these provide an interpretation of storage (essentially time-independent deformation in a spring), and dissipation (time-dependent dashpot movement). The elastic modulus is E, relating stress and strain, with viscous movement (or "flow") governed by the viscosity μ, relating stress and strain rate. The elements can be linear or nonlinear with stress. If linear, the moduli are constant and the units are Pa and Pa·s respectively.

Ice exhibits a wide range of material responses and as a result is a very interesting material to study. It is particularly prone to viscoelastic movements, with a high degree of time-dependence, as well as to fracture. It is prone also to change its microstructure under stress, and the resulting effect on its mechanical response is highly significant.

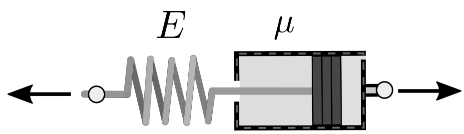

Figure 1.1 Spring and dashpot: basic mechanical elements for material modelling.

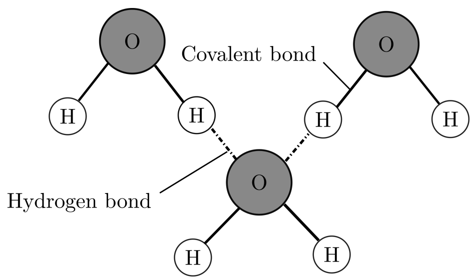

Figure 1.2 Bonds in ice crystal.

Its mechanics serve as an extreme which provides an excellent basis for studying and understanding material response. Despite the complexity of ice behaviour, engineers must devise ways to design engineering structures and vessels to resist ice forces. The approach taken in this work is to rely on a combination of basic knowledge and field measurements, with empirical interpretation of data and measurements.

A significant amount of engineering research took place in Canada during the 1970s and 1980s. This included a series of highly imaginative experiments such as the use of instrumented icebreakers in ramming of hard ice features and iceberg bergy bits, the Hans Island experiments, the Molikpaq instrumented platform in the Beaufort Sea, and experiments involving medium scale indentation of ice in the field. These experiments led to an important increase in knowledge as reported in the present work.

1.2 The Ice Crystal

Bonds will cause atoms to combine into molecules and thereby into liquids and solids. The main forms of bond between atoms are ionic, covalent and metallic. A covalent bond is formed when the valence electrons from one atom are shared between two or more atoms. The water molecule H_2O consists of two covalent bonds between the oxygen atom and each of the two hydrogen atoms. In water and ice there are much weaker hydrogen bonds between the H_2O molecules themselves, and the number of these decreases with increasing temperature of water. Figure 1.2 illustrates the two kinds of bonds. Liquid water molecules are in constant motion and will have on average fewer than 4 (generally between 3 and 4) possible hydrogen bonds. In ice, water will form all 4 possible hydrogen bonds because the molecules in a solid are locked in a fixed crystal lattice. As water is heated, the heat added contributes to loosening, distorting or breaking the hydrogen bonds. About 10% of the hydrogen bonds break upon melting.

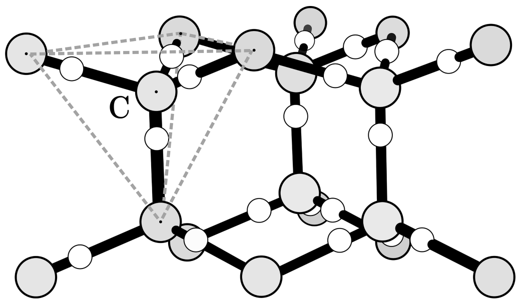

Figure 1.3 Ice crystal structure: basic unit showing positions of atoms.

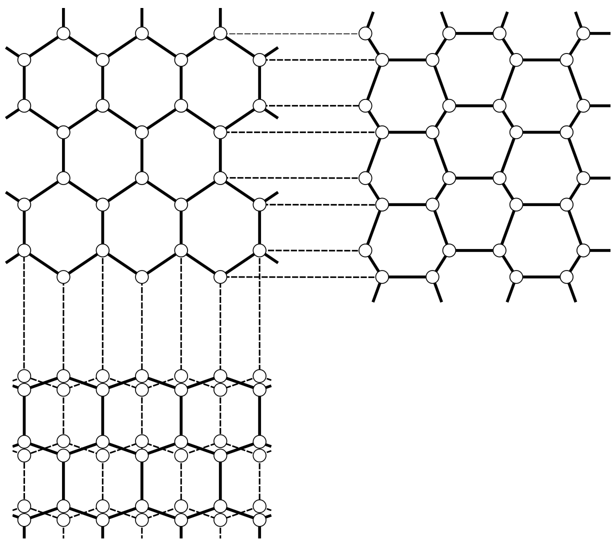

Figure 1.4 Ice crystal: different perspectives.

Ice Ih, the familiar "ordinary ice" is the hexagonal form found on earth. (Other forms do exist, for instance ice Ic under high pressure; see, for example Schulson and Duval, 2009. These are not relevant to the present work.) Figure 1.3 illustrates the arrangement of the oxygen and hydrogen atoms into a hexagonal structure, with Figure 1.4 showing the arrangement looking from different directions. A useful representation is obtained by considering a particular oxygen atom, say "C" in Figure 1.3, and its four nearest neighbours, which are shown by broken lines that are joined to the atoms surrounding "C" in the figure. This very closely forms a tetrahedron with C at its centre. An excellent first approximation to the geometry is obtained by considering the oxygen atoms as being arranged in a set of regular tetrahedra; see also Pounder (1965) and Schulson (1999). Some tetrahedra will point down as shown in Figure 1.3; others will point upwards. Figure 1.4 shows different perspectives of the ice crystal.

The c-axis of the crystal is along the axis of the hexagon while the basal plane is at right angles to this axis, as shown in Figure 1.5. To emphasize, the oxygen atom of each molecule is strongly bonded to two hydrogen atoms by covalent bonds, while the molecules are weakly bonded to each other by hydrogen bonds. The hydrogen atoms

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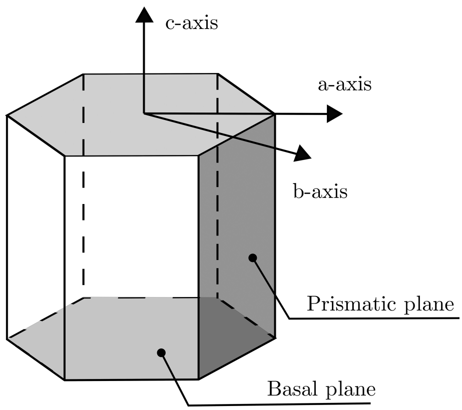

Figure 1.5 Crystallographic planes and axes.

do not lie midway between two oxygen atoms, but are closer, and more bonded, to one of the two. This leads to uncertainty and an increase in entropy. The distance between two adjacent oxygen atoms is 0.275 nm.

Associated with the anisotropy is the property of double refraction and birefringence. As a result of this, interesting details can be found regarding the microstructure using thin sections of ice samples viewed through crossed polaroids. These include the crystal structure, microcracking and recrystallization, all very important in the present work. Details of this technique can be found in Pounder (1965) applied to ice and more generally in mineralogy textbooks. The use of the universal stage to obtain crystal orientation is noted. The research carried out by the author and reported in this work generally followed as far as possible the demanding methods of Sinha (1977) in preparing thin sections and studying crystal structure. Sinha also pioneered the use of side lighting across the thin sections to identify cracking and microcracking. These tools were instrumental in discovering the effect of stress history on microstructure under various states of stress. Examples of thin sections can be found in Chapter 7 (Section 7.4) and in colour in Melanson et al. (1999) and especially in Meglis et al. (1999).

1.3 Ice on the Earth

Ice exists on earth at high homologous temperature. For ice at –10°C (263 K), the homologous temperature T_m is 263/273 = 0.96. The fact that water expands upon freezing results in masses of ice floating on water. Both water and ice have unusually high values of specific heat capacity, as compared to soil and rock, taking much longer to warm in summer, and to cool down in winter. As a result, water and ice provide a thermal stabilizing effect on the climate. Milder temperatures result in maritime regions. In the arctic and antarctic cryosphere, cold temperatures persist, aided by the high albedo associated with the snow and ice cover. The floating ice at the same time presents a hazard—and a challenge—to shipping and to construction in offshore regions.

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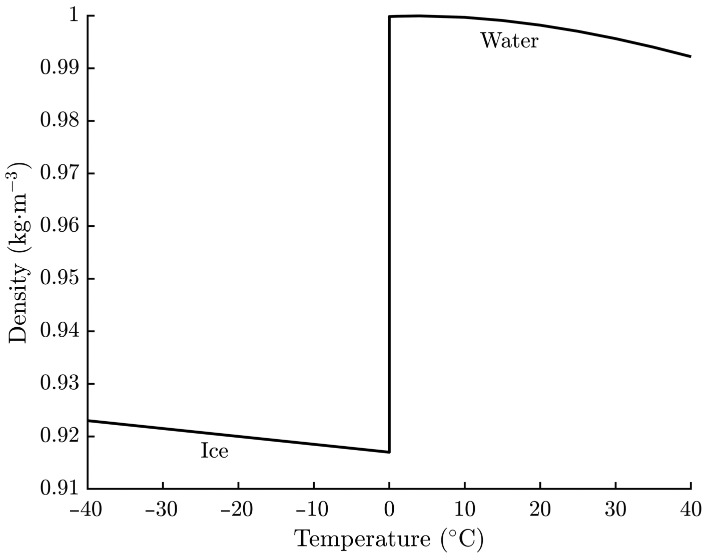

Figure 1.6 Density of ice and water at atmospheric pressure.

We give here an overview of ice on earth. Detailed descriptions can be found for example in Pounder (1965), Sanderson (1988), and Weeks (2010). As noted in the preceding section, ice on earth is in the form of hexagonal crystals. We consider first freshwater ice and then sea ice, starting with the freezing process of pure ice and water. The density of ice and water varies considerably with temperature as shown in Figure 1.6. Pure water expands about 9% upon freezing, a large amount even compared to other materials that expand upon freezing. This can cause huge pressures to develop in sealed containers of water that are then frozen. Figure 1.7 shows the density variation of water near the freezing point. It is seen that the maximum density occurs at 4°C, termed the inversion temperature. At this temperature, clusters of crystalline ice form, which have lower density than the surrounding water molecules, thus resulting in a decrease of density with temperatures below 4°C. When a body of water at a temperature greater than 4°C is cooled by the air at a lower temperature, the cooled water is more dense and sinks. This vertical circulation continues until the water reaches a uniform temperature of 4°C. If the water is cooled further, the density is reduced so that the vertical (convective) circulation ceases. Further heat transfer is by conduction, a much slower process. Ice will then form on the surface, and ice cover will develop. The temperature at the bottom of the ice will be 0°C, and the water will have a gradient from 0°C to 4°C, termed the thermocline, below which the water is at 4°C. Wind, wave and current will modify and complicate this idealized picture.

The presence of salt in water modifies the situation considerably. The salinity of sea water is relatively constant at 35 parts per thousand, denoted 35‰. (There are some exceptions such as the Baltic and Caspian Seas, which are brackish.) Both the temperature of maximum density and the freezing point decrease with salinity, the first at a greater rate, so that at salinities greater than about 25‰, sea water has maximum density at the freezing temperature. There is no temperature inversion and cooling of

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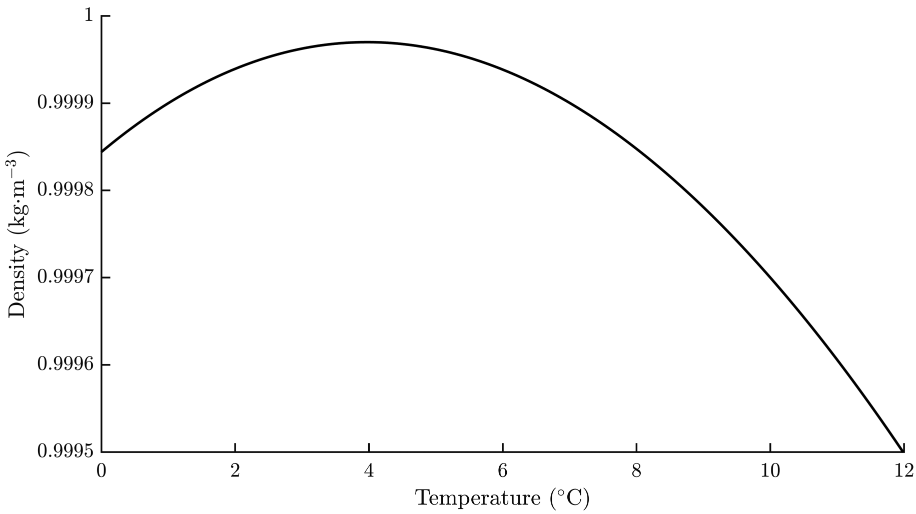

Figure 1.7 Density of water near 4°C.

the ocean surface by a cold atmosphere will result in the surface water being more dense. As a result, convection will continue down to the freezing point and the whole body of water must be reduced to freezing point in order to form ice. Ice cover does not form as in freshwater lakes. Only under very cold conditions with protracted periods of low temperature, such as at high latitudes, will ice form on the sea. This is well known in arctic conditions, which will now be discussed.

The term "young ice" refers to ice that is 10 to 30 cm in thickness, formed recently.[1] First year ice is floating ice of no more than one year's growth, developing from young ice; thickness is from 0.3 to 2 m. It is usually level where undisturbed by lateral pressure. Currents and winds cause the ice floes to interact with each other, resulting in pressure ridge formation. The ridges are made up of angular ice blocks of various sizes that pile up onto the floes. The part above the water level is the sail and that under the water level is the keel. Grounded ridges are termed stamukhi. First year ice features that are ridged can be rough and irregular, although linear in plan. Second year sea ice has not melted in its first summer. By the end of the second winter, the thickness might be 2 m or more. Summer melting results in smoothed and rounded ridges and hummocks.

First year (FY) sea ice generally has a columnar structure (Pounder, 1965; Sanderson, 1988). In the initial freezing on the water surface, small platelets of ice form, generally less than a millimetre in thickness and a few centimetres in width. This is termed frazil, or frazil ice. The c-axes are aligned at right angles to the plane of the platelets, and are generally pointed vertically. Large numbers of these form with c-axes parallel and pointing vertically. These act as seed crystals for the continued growth of ice. The crystals, or grains, which grow perpendicular to the c-axis grow more rapidly

[1] With regard to nomenclature, there are various national standards. The WMO Sea Ice Nomenclature is one useful source.

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than those which grow in the direction of the c-axis and predominate in the further growth of the ice sheet. The result is that columns of ice form with c-axes pointing horizontally, so-called columnar ice. This ice is referred to as S2 ice if the c-axes are randomly oriented but in the horizontal plane. S1 ice has vertically oriented c-axes, and S3 denotes ice with the c-axes in the horizontal plane but oriented in a particular direction (Schulson and Duval, 2010). As the ice freezes, pockets of brine form between the platelets. Most of this is initially within the grains, but it soon begins to drain in brine drainage channels. This drainage is from cold to warm, along the temperature gradient, generally downwards given a cold surface temperature. The brine content can be calculated from the temperature and salinity.

Multiyear (MY) ice is generally defined as having survived at least two summer seasons (but some sources define it as having survived a single melt season). It is typically 2 to 4 m thick and may thicken if more ice grows on its underside. Extreme ridge thicknesses can be many times the values just quoted and are a subject of probabilistic analysis for fixed offshore installations, in terms of the thickness, number of interactions and related parameters. The ridges will be smoothed compared to FY ice as noted above. We have discussed columnar ice structure; granular ice is composed of crystals with approximately equal dimensions. Brine inclusions may exist as irregular pockets at grain boundaries. Optical axes (or c-axes) are randomly oriented. Equiaxed crystals are crystals that have axes of approximately the same length, as may be the case with laboratory-grown ice. Equiaxed grains can often be an indication of recrystallization. “Statistical isotropy” is often a useful assumption in analysis. In this assumption, the material is treated as being an isotropic material, essentially by averaging over a set of crystals or grains. An analysis of S2 columnar and of granular ice with regard to the relation between the overall behaviour and that of single crystals has been given by Schapery (1997a).

Two other ice features should be noted as being of significant engineering importance as a potential hazard to ships and engineering. These are icebergs and ice islands. Icebergs are generally large masses of freshwater ice which have broken away from glaciers, a process referred to as “calving”. Large icebergs are a potential hazard to offshore activities as are smaller pieces such as bergy bits especially if accelerated by waves in high sea states. A standard has been adopted by the IIP and the Canadian Ice Service for iceberg size classification. The corresponding waterline lengths are 0–5 m (growlers), 5–15 m (bergy bits), 15–60 m (small icebergs), 60–120 m (medium icebergs), 120–215 m (large icebergs) and greater than 215 m (very large icebergs). Icebergs can break up further, and, as noted, the resulting fragments also cause a potential hazard, especially in high sea states where they might be difficult to detect. Tabular bergs (flat-topped) and ice islands generally form from ice shelves. The ice islands may be up to 50 m thick and hundreds of square kilometres in area.