

SCHULSON, E.M. and P. DUVAL. 2009. *Creep and fracture of ice*. Cambridge, etc., Cambridge University Press. 401pp. ISBN-10: 0-521806-20-6, ISBN-13: 978-0-521-80620-6, hardback, £69/US\$134.

Aimed at graduate students and researchers in the fields of glaciology, engineering, earth and planetary science and materials science, this book is crammed with information; just about every paragraph has something important to say and is worthy of careful reading. A browse through the contents provides the first hint of the thorough and comprehensive account that is to follow, and the introduction (chapter 1) consists principally of a synopsis so that the reader has a good idea of what is coming. I like the list of other 'text books' at the end of this chapter, and in fact all chapters and many smaller sections throughout the book end with excellent brief summaries that also provide references for further reading. The chapter 1 summary might also have listed the principal journals containing the bulk of the relevant literature, although this can be picked up from a browse of the references at the end of each chapter. I would have liked a table of symbols either at the front or back of the book. Chapters 2–4 are concerned with structure, microstructure and physical properties, and provide necessary and excellent background to what follows. Chapters 5–8 deal with ice creep (chapter 8 covering high-pressure and planetary ice) and chapters 9–13 with ice fracture. Chapter 14 deals with ice/structure interactions and, finally, chapter 15 concerns sea ice.

Chapter 2, on the structure of ice, contains the best description I have read of molecular stacking. It provides the fundamentals of dislocations and introduces the concept of the glide plane (important for later in the book). While it defines lattice parameters, 'c', as the displacement along the c-axis, it neglects to define 'a' as the displacement along the a-axis. A very good explanation is provided of plane defects (e.g. grain boundaries) and volumetric defects (e.g. bubbles, clathrate hydrates).

Chapter 3 describes different ice types (glacial, sea/river ice, hail, etc.) and techniques for studying their microstructure. Techniques include optical microscopy, X-ray microtomography, scanning electron microscopy, Raman spectroscopy and electron backscatter diffraction. No mention is made here, or elsewhere in the book, of the history of ice structure studies (surely the Rigsby stage deserves a mention!) or of the automatic ice crystal fabric analysers that have become available over the past 5–10 years. The chapter includes sections on nucleation and crystal growth within river and sea ice.

Much of chapter 4 provides fundamental information on the elastic properties, which can be found in many texts. That is not to say it is unwanted here; to the contrary, it is fundamental information for the student of ice rheology. Elastic constants, Hooke's law, Young's modulus, etc., are covered, including application to polycrystals (and a table of values of properties for isotropic ice). The extension (no pun intended) is then made to deformation and recrystallization textures, to sea ice and to snow and firn. The second half of chapter 4 deals with the kinetic friction of ice sliding upon itself, and finally with molecular diffusion.

Chapter 5 is the first to deal in detail specifically with ice creep (plastic deformation), and it is about single crystal creep, including the importance for internal friction of basal slip, the orientation of the crystal and impurities. Data are

provided and an empirical flow law is given for basal slip (a few of the data references are missing from the list at the end of the chapter, i.e. those listed in fig. 5.8). The remainder of the chapter concerns the dynamics of dislocations (including rate-limiting processes) and rate-controlling processes for single-crystal deformation.

The creep of polycrystalline ice, including the laboratory data and rate-controlling processes, is covered in chapter 6. Creep test data are shown and stages of the creep curve are described in detail, including effects of temperature, grain size, impurity content and confining pressure. Tertiary creep is explained, including the establishment of a constant strain rate (constant stress experiments), and the evidence for a stress-dependent recrystallized grain size. I personally prefer the term 'accelerating creep' rather than 'tertiary creep' to describe the section of the creep curve between minimum and constant tertiary creep. The ice deformation experiments are well described, and at the end of the chapter recrystallization textures are nicely described. However, the link between the two is not made strongly enough, or, at least, one needs to jump 15 pages (from p. 115 to p. 130) to find it. The important point is that it is the development of the fabric that is responsible for the accelerating creep. In the middle of the chapter, out of place in my opinion, is a section on creep of columnar ice. This is followed by a detailed description of rate-controlling processes, a topic that Duval has led for three decades. There is a well-written and informative section on grain growth (in the laboratory and in polar ice sheets) and on recrystallization, leading finally into crystal fabric and texture in laboratory and glacial ice.

Chapter 7 deals with modeling the ductile behavior of ice, including texture development. The visco-plastic self-consistent approach to modeling isotropic and anisotropic ice flow is described in detail. In this approach the average stress and strain rate over all grains must coincide with the overall stress and strain rate at the boundary. While for isotropic ice this may be satisfactory, for anisotropic ice the second moments of the stress and strain rate also need to be considered and fast Fourier transform models are outlined for this problem. There is (again) a section on columnar ice deformation (visco-plastic) modeling. The second half of chapter 7 includes some methods for expressing the strength of crystal orientation fabrics (Duval uses the term 'texture', which to me includes crystal orientation fabric, size and shape; only fabric is discussed here), a very good description of the mechanisms of fabric development, some results of fabric simulations and a comparison of different fabrics from polar ice sheets. The chapter concludes with a brief section on modeling anisotropic ice flow (the Schmid factor is mentioned, but without definition here or earlier) and a comparison of model and laboratory results, leading to the idea of self-consistent models.

Chapter 8, the final and briefest chapter dealing with creep, is about high-pressure ice and planetary ice. While the rest of the book deals with ice Ih, the only naturally occurring ice on Earth, this chapter deals with ice that occurs on the outer and large icy planets. Mechanical properties of ice II, III, V and VI are discussed. Experiments under the high pressures required to study these ices are difficult and a description of experimental techniques is provided. The visco-plasticity of the different ices, including grain-size effects, is discussed and finally a note is included on the flow of methane clathrate hydrates and ice in the ammonia–water system.

Chapter 9, the first to deal with higher strain rates thus resulting in fracture, provides the first principles of linear elastic fracture mechanics, beginning with and later building on Griffith's energy-balance assumptions. Theory concerning generation and propagation of cracks is introduced. Much of the chapter then deals with defining and measuring fracture toughness, and with the effect on fracture toughness of temperature, grain size and texture, porosity, particulate content, etc. The chapter concludes with short sections on the fracture toughness of snow and comparing concrete, ceramics, laminates, polymers, etc.

Chapters 10–12 deal with the brittle failure of ice under tension, unconfined compression and confined compression respectively. After short sections on tensile strength measurement techniques and on single-crystal tensile strength, most of chapter 10 concerns polycrystalline ice. There is a description of the experimental suite of results on the effects on tensile strength of temperature, strain rate, grain size, damage, texture, brine inclusions (relevant to sea ice, later in the book) and laboratory sample size. A section on the ductile to brittle transition is followed by a discussion of strength-limiting mechanisms, again with a short section on single crystals followed by a longer section on polycrystalline ice. The dominant effect on crack nucleation and propagation is grain size, which receives detailed attention.

Brittle compressive failure is more complicated than under tension, due to the interaction of cracks leading to macroscopic faults and due to frictional sliding. Chapter 11 begins with a detailed description of laboratory techniques for measuring unconfined compressive failure. A comparison between ductile and brittle behavior notes that brittle compressive strength is higher than tensile strength, and this affects the strain rate at which the transition from ductile to brittle behavior occurs. As above, this chapter also contains a brief note on single-crystal behavior (temperature, strain-rate and orientation affected). This is followed by a longer section on polycrystalline ice covering effects of strain rate, temperature, texture, grain size, porosity/salinity, damage, cyclic loading and size/boundary conditions. Most interesting for me in this chapter, however, is the second half, dealing with failure processes. In this and the next section, wing cracks (Schulson is famous for his experimental work on this topic) are introduced and explained in detail.

A lengthy chapter 12 begins with experimental techniques and results of confined compression experiments (biaxial and triaxial loading) on granular ice and columnar ice. Brittle compressive failure envelopes for columnar freshwater ice and sea ice are presented, and Coulombic shear faults are introduced and developed mathematically two sections later; in between, a short section on failure surfaces interprets the results. A section on the nature of plastic faults is followed by a long section on Coulombic shear faults, including details of wing cracks and comb cracks. Processes leading to spalling are described (wing cracks are again involved). The final sections of the chapter deal with mechanisms occurring after the ice has failed. Being confined, it still possesses strength and its ductile or brittle response, failure envelope and friction are outlined.

Chapter 13 again examines the ductile to brittle transition in compression, now in more detail. A micromechanical model based on the concept of a competition between creep and fracture is presented and compared with observations (on freshwater ice and sea ice) in terms of grain size, confinement and damage. The chapter ends with a comment on 'dirty ice' and an application to rocks and minerals.

Physical processes involved in the indentation fracture of ice interacting with other structures (e.g. a bridge or lighthouse) are examined in chapter 14. The ductile to brittle transition is examined in detail, including two models again based on the concept of a creep/fracture competition; it is important because the transition strain rate seems to depend, by orders of magnitude, on scale over the range 1 m (in the laboratory) to 100 m (e.g. a sea-ice field). Brittle failure is discussed in two modes, edge-loaded plates (consider a load on a sea-ice floe) and indented walls (e.g. an iceberg collision with a fixed structure). The unexpected finding more than 20 years ago that failure pressure decreased with increased contact area is examined and explained, and the chapter concludes with a short section on impact failure.

The final chapter, chapter 15, concerns (Arctic) sea ice. A prologue states that figure 15.1 shows examples of wing cracks within the sea ice. I cannot clearly see them, but they are very clear in figures 15.3 and 15.5. The first sections of this chapter provide observations and an interpretation of fracture features (wing- and comb-like cracks) in seasonal sea ice. Proposed mechanisms for fault initiation in sea ice are presented and further analysis described. The rheology of the winter sea-ice cover is examined separately, including nested failure envelopes and viscous flow. Finally, the ductile to brittle transition in sea ice is briefly considered, and also the independence of scale. The book's front cover has a picture of emperor penguins crossing, on their bellies, a refrozen lead within a sea-ice covered area. Not being largely landlocked like the Arctic, the Antarctic sea ice is more divergent, leading to the main differences in the deformation characteristics. Despite the cover picture, the book states that it deals only with the fracture of Arctic sea ice. While the large-scale sea-ice dynamics in the two polar regions may differ, the small-scale rheology applies equally to Antarctic (or any other) sea ice. I see no need for the distinction here, and while there is this distinction the book seems to lack completeness.

The presentation is clear and readable, with few editorial errors. There are not many reference books dealing with the flow and fracture of ice. To my knowledge, this is the most comprehensive, and the first to comprehensively cover the topic from a laboratory approach. This book will be relevant for years to come. It is important and recommended reading for all students and researchers of ice mechanics, physics and engineering.

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