Ice Forces on Structures

An Online Continuing Education Course for Engineers

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Credit: 3 Hours / 3 PDH / 3 CPD

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Introduction

Any structure placed in an environment where the presence of ice is a hazard to its integrity and stability needs to be designed to withstand the forces generated by ice moving against it. A designer should also consider how the cold may affect the intended operations of a structure, because freezing of ice may hinder some of the normal warm weather operations. These guidelines presented in this course are intended for structures placed in inland waters, e.g., lakes, rivers, and coastal waters.

An ice sheet moves under the influence of shear stresses imparted by wind and water and by thermal expansion (as long as the ice sheet is intact). It transmits the accumulated forces to a structure situated in its path. The shear drag forces attributable to wind and water can be transmitted over large distances through an intact ice cover. In many situations, these environmental forces can be large, and the ice sheet fails during its interaction with a structure. The ice failure process limits the large environmental force being transmitted to the structure. Unless the environmental forces can be estimated with confidence to be small, the methodology to estimate ice forces from floating ice is generally to determine the forces required to fail an ice sheet in the vicinity of a structure. An ice sheet fails by crushing, splitting, bending, buckling, or a combination of these modes. For a given failure mode and structure shape, theoretical formulations or experimental results, along with ice properties, are used to estimate the forces required to fail an ice sheet. The forces are estimated for one, two, or all possible failure modes, and the failure mode with the lowest estimated force is assumed to occur at the ice-structure interface. At times, it may be necessary to conduct model tests to simulate an ice-structure interaction to determine the interaction forces. Attention should also be given to the clearance of broken ice pieces, because the advancing ice sheet will interact with the broken pieces if they accumulate in front of the structure. It is also possible that the accumulation of broken ice pieces may freeze together to form a grounded collar, which may provide some protection from further ice movement.

In situations where an ice cover is made up of drifting ice floes, the impact of these floes causes a horizontal force on a structure. (Although impact from a drifting iceberg falls into this category, we will limit our discussion to drifting ice floes.) The forces generated when ice floes strike a structure depend on the mass and the initial velocity of the floes. If the kinetic energy of the moving ice floes is greater than the work done in failing the ice along the entire width of the structure, the design force is then limited by the ice failure processes mentioned above. If the kinetic energy and the momentum of drifting ice floes are small, resulting in indentation of the structure into the ice floes over a part of its width, ice forces are estimated from balancing the momentum and the energy before and after an impact.

The methodology given in this course for estimating ice forces is based on the results of theoretical and experimental research in ice mechanics and measurements of ice forces in the field. Most recently, our understanding of processes active during crushing of ice at various indentation speeds has been increased. The CSA and the AASHTO codes consider dynamic and static loads on bridge piers located in rivers, lakes, and coastal waters. The dynamic loads develop when moving ice fails against a pier during spring break up, or when currents and wind move ice sheets past piers at other times of the year.

The static loads are generated by thermal expansion or contraction of the ice and by fluctuations in the water levels.

Mechanical Properties of Ice

Introduction.

Because the forces necessary to fail an ice sheet depend on the mechanical properties of ice, the mechanical properties of the freshwater and sea ice are briefly reviewed below before methodologies to estimate the ice forces on a structure are given. Ice is a unique material. In the temperature range under which it is normally encountered, it is very close to its melting point. Ice can creep with very little applied stress, or it can fracture catastrophically under a high strain rate.

There are two primary ways to categorize ice. One is based on the melt from which the ice is grown (freshwater or sea water), and the other is based on the size of the ice blocks (i.e., large ice floes or accumulations of broken ice in a random ice rubble). The conditions under which ice forms will determine its grain structure, with common forms being frazil ice, columnar ice, discontinuous columnar ice, and granular ice. Both the porosity within the ice and the grain structure significantly influence the mechanical properties of the ice. Various books (e.g., Michel 1978, Ashton 1986, Cammaert and Muggeridge 1988, Sanderson 1988) cover the subjects of formation and types of ice, as well as ice properties.

The porosity attributable to brine and air pockets affects the ice properties. The brine volume v_b ($^o/_{oo}$) is obtained from the following relation (Frankenstein and Garner 1967):

$$v_b = S_i\,(0.532 + 49.185/|T|) \qquad (1)$$

where S_i ($^o/_{oo}$) = salinity, T (°C) = temperature of the ice, and the symbol $^o/_{oo}$ refers to parts per thousand.

The porosity ascribable to air can be obtained from the following relation after the bulk density ρ of ice containing salt and air are measured (Cox and Weeks 1983)

$$V_a/\,V = 1-\rho/\rho_i + \rho S_i F_2(T)/F_1(T) \qquad (2)$$

where

V_a = volume of air
V = bulk volume
ρ = density of pure ice
S_i = salinity of ice
$F_1(T)$ and $F_2(T)$ = functions of temperature derived from a phase equilibrium table (Cox and Weeks 1983) and given in Figure 1.

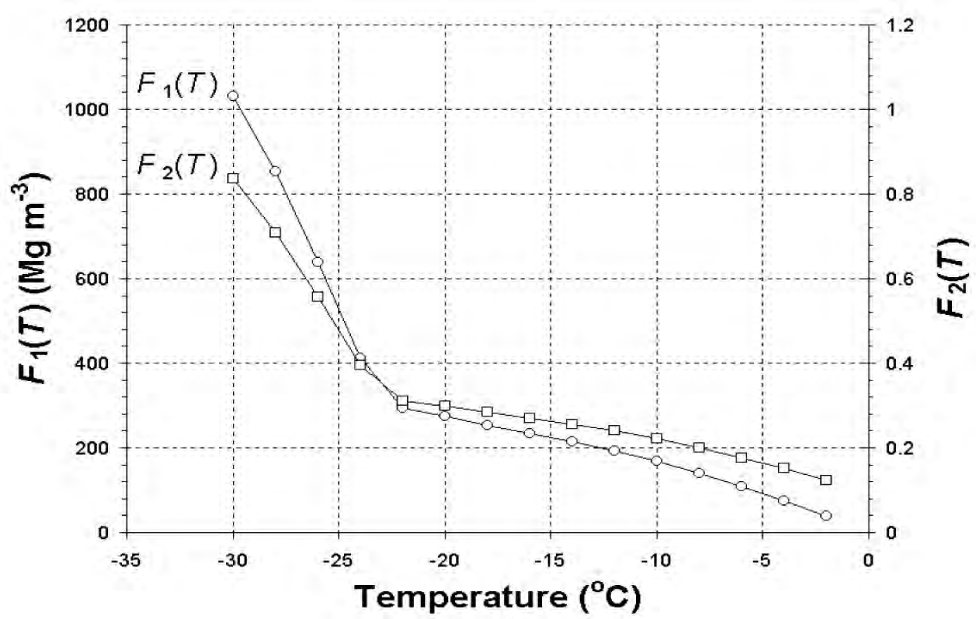

Figure 1. Plots of *$F_1(T)$* and F_2(T) with respect to temperature. To convert degrees C to degrees F use the following: °F = °C x 1.8 +32.

Compressive Strength. Values of the uni-axial compressive strength for ice range from 0.5 to 20 MPa (72.5 to 2900 psi). The strength is a function of strain rate, temperature, grain size, grain structure, and porosity. Analyses of strength measurements have shown that the strength increases with strain rate, up to a rate of 10^{-3} s^{-1} , whereupon the strength generally decreases at higher strain rates because of brittle fracture.

In the lower strain rate range below 10^{-3} s^{-1}, the compressive strength of freshwater ice is given by (Sinha et al. 1987)

$$\sigma_c = 212\dot{\varepsilon}^{0.34} (3.07 \text{ x } 10^4 \dot{\varepsilon}^{0.34}) \quad (3)$$

where σ_c is in MPa (psi) and $\dot{\varepsilon}$ is in s^{-1}.

The above expression is for the compressive strength of ice at -10°C (263 K or 14°F). The compressive strength at another temperature T(K) can be obtained by multiplying the strength at -10°C (14°F) by a correction factor $[\exp\{(Q/R)(263-T)/(263T)\}]^{1/3}$, where Q = 65 kJ mol^{-1} (61.6 Btu mol^{-1}) (the activation energy for columnar ice) and R = 8.314 J mol^{1} K^{-1} (1.986 Btu lb^{-1} mol^{-1} R^{-1}) (the universal gas constant).

For sea ice, the following equations for compressive strength were derived from an analysis of over 400 small sample tests (Timco and Frederking 1990). These equations are:

$$\sigma_c = 37\dot{\varepsilon}^{0.22} \lfloor 1 - (v_T/270)^{0.5} \rfloor \text{ for horizontally loaded columnar sea ice} \quad (4)$$

$$\sigma_c = 160\dot{\varepsilon}^{0.22} \lfloor 1 - (v_T/200)^{0.5} \rfloor \text{ for vertically loaded columnar sea ice} \quad (5)$$

$$\sigma_c = 49\dot{\varepsilon}^{0.22} \lfloor 1 - (v_T/280)^{0.5} \rfloor \text{ for granular sea ice} \quad (6)$$

where $\dot{\varepsilon}$ is the strain rate in s^{-1}, and υ_T is the total porosity in the ice (brine and air) in parts per thousand. The range of strain rate for these equations is 10^{-7} to 10^{-4} s^{-1}. Above this strain rate, the ice can experience brittle failure with compressive strengths exhibiting a wide range of variability.

Flexural Strength. The flexural strength is generally lower than the compressive strength. Measurements on freshwater ice range from 0.5 to 3 MPa (72.5 to 435 psi), with an average of 1.73 MPa (for temperatures less than -5°C (23°F) (Timco and O'Brien 1994). There is very little temperature or strain rate dependence, but there is a wide scatter in the measured flexural strength with higher values from smaller samples. At temperatures close to 0°C (32°F), the strength of freshwater ice can be essentially zero if solar radiation has caused pronounced "candling." For sea ice, Timco and O'Brien (1994) compiled the results of over 900 flexural strength measurements to obtain the following dependence of the flexural strength on the brine volume.

$$\sigma_f = 1.76 e^{-5.88\sqrt{\upsilon_b}} \quad (255\, e^{-5.88\sqrt{\upsilon_b}}) \qquad (7)$$

where σ_f is in MPa (psi) and v_b is the brine volume fraction. The strength value for zero brine volume (1.76 MPa or 255.3 psi) agrees with the average value of 1.73 MPa (250.9 psi) determined from tests on freshwater ice.

Fracture Toughness. The fracture toughness depends on the loading rate and the ice type, with less variation ascribable to temperature and grain size. Typical values for freshwater ice range from 109 ± 8 kPa $m^{0.5}$ (0.01581 ± 0.00116 ksi $in.^{0.5}$), for columnar-grained S2 ice, to 151 ± 12 kPa $m^{0.5}$ (0.0219 ± 0.00174 ksi $in^{0.5}$) for granular ice (Weber and Nixon 1992). In-situ measurements of the fracture properties of lake ice and sea ice revealed that fracture toughness depends on the size of the specimen, and that its range is 50-250 kPa $m^{0.5}$ (0.00725 to 0.03626 ksi $in.^{0.5}$) (Dempsey et al. 1999a,b)

Elastic Modulus. Ice deformation involves elastic and creep processes, and the large-scale modulus is usually discussed in terms of an "effective modulus" that incorporates these processes. This modulus is a strong function of loading rate, temperature, and grain size and type. The values of elastic modulus range from approximately 2 GPa (2.9×10^5 psi) at low frequency loading to a high frequency value of 9 GPa (1.3×10^6 psi) (Sinha et al 1987, Cole 1995a,b).

Broken Ice Properties. Ice rubble is usually assumed to behave as a linear Mohr-Coulomb material, for which the shear stress τ and the normal stress σ_n on a failure plane are related by

$$\tau = c + \sigma_n \tan \o \qquad (8)$$

where c is the apparent cohesion and $\o$ is the effective angle of internal friction. Recent studies (Prodanovic 1979, Ettema and Urroz-Aguirre 1991, Loset and Sayed 1993, Cornett and Timco 1996) have shown that the yield envelope is non-linear but can be approximated with a linear envelope for a limited range of conditions; that cohesion is negligible for unconsolidated rubble; that $\o$ depends on the stress history and decreases with increasing pressure; that $\o$ is less than the maximum angle of repose; and that $\O$ depends on the strain path and pressure. Measured values of $\o$ range from 20° to 45°.

Environmental Forces

Wind and Water Drag Forces. The drag force, caused by wind and water shear stresses on the top and bottom surfaces of an ice cover, can be estimated from the following expression:

$$F_d = C_d \rho A V^2 \qquad (9)$$

where

C_d = drag coefficient
ρ = density of air or water
A = fetch area
V = veloc … n ice cover.

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When an ice sheet is restricted from expansion from four or two sides, the confinement causes, respectively, biaxial or uniaxial stress (Sanderson 1984, 1988). The method of calculating thermal ice force in a confined ice sheet is as follows.

Calculate temperature change as a function of depth, taking into account heat transfer by conduction, radiation, and convection.