ICE LOADS ON STRUCTURES

Robert Frederking
National Research Council of Canada, Ottawa, Canada

Karl Shkhinek
Saint Petersburg State Polytechnical University (SPbSPU), Russia

Keywords: Ice forces, ice conditions, ice loads, Tensile Strength, Shear Strength. Friction, Ice Ridges, Ice floe.

Contents

Summary

Ice of many forms grows annually on rivers, lakes and the sea, and as a consequence can interact with hydrotechnical or coastal structures, generating forces on them. These forces must be appropriately assessed and accounted for in the design of structures in water bodies affected by ice. Ice conditions such as thickness, strength, morphology and floe size must be determined and suitable extreme values of these features determined. The environmental driving forces of wind, current and temperature must also be understood. Combining information on ice conditions and environmental factors, this chapter provides guidance on calculating the magnitude of ice forces that a structure might be expected to withstand over its lifetime.

1. Introduction

In cold climates the ice that forms each winter in rivers, lakes or seas must be taken into consideration in design and operation of structures placed in such waters. Examples of structures include bridges, wharves, docks, jetties, locks, dams, etc. In this chapter only the environmental loads due to floating ice will be considered. Other aspects of loading on these structures such as traffic, earthquakes, etc. are not considered here, but are important factors which cannot be ignored.

In nature, ice can occur in various forms; level ice sheets grown on the surface of calm water, broken ice pushed together into larger accumulations which partially refreeze into ridges or rubble, frazil ice generated in fast flowing water which can attach itself to structures. Environmental driving forces; wind, current, temperature, etc. cause ice to move interacting with structures and developing horizontal and vertical acting ice loads. As a material, ice is weaker than the materials in structures, and can fail in various ways such as crushing, bending or splitting. By combination of the geometry of the structure, size of the ice and, in spite of the limited strength of ice, sufficient ice forces can be generated to fail structures. Therefore careful consideration of ice loading must be taken for any structure exposed to ice.

Equations will be presented for calculating ice loads under various conditions. Use of ice loads determined from equations presented in this chapter for design of structures should make reference to national or regional codes of practice in terms of appropriate levels of safety and reliability for structures are followed.

2. Assessment of Ice Conditions

In considering a structure in an area where ice may be present, the first step is an assessment of possible ice conditions. Ice may form every year or it may be a relatively rare occurrence, happening only once every 10 years or even 100 years. In any case an assessment of ice conditions must be made and a critical design ice condition defined. Climatic information on the ice thickness, air temperatures, snow fall, wind speed and direction and current speed can be obtained by direct measurement or from national or regional meteorological, hydrological or oceanographic services. Ice in its simplest form is level and of uniform thickness, however it may be broken up and pushed together into ridges which partially refreeze. It may be broken into individual floes of varying size and thickness, drifting at varying speed, acted upon by wind or current, or subject to temperature changes. In order to calculate ice loads on a structure any or all of these factors of ice conditions must be known, and critical conditions likely to be encountered over the lifetime of the structure determined.

Requirements for specifying ice conditions will be explored in greater detail in following sections of this chapter. Also *Instrumentation and Measurement Techniques in Ice Studies*, provides guidance on measurements of ice conditions, if such information is not at hand.

3. Ice Interaction Scenarios

Interactions between various ice features and a structure give rise to ice forces. The size and shape of the structure, the ice conditions, and the environmental driving forces can result in a number of different interaction scenarios, failure modes and resulting ice forces. The factors influencing the scenarios can be categorized into ice feature characteristics, ice properties, limiting mechanisms, interaction geometry, all culminating in failure modes. These factors will now be expanded upon in more detail.

3.1. Ice Feature Characteristics

Ice feature characteristics have to be specified in a quantitative manner, as appropriate to the environment, and include the following:

- Level ice; thickness, floe size and drift speed. At the very least the values expected to produce the largest ice forces expected to be encountered over the lifetime of the structure must be specified, and ideally probability distributions of them should be determined.

- Rafted ice; quantifying this type of ice requires the number of layers, total thickness, degree of refreezing of the layers, floe size and drift speed. Again, at least a likely combination of values to produce the largest ice force, and ideally distributions are needed.
- Ridges; these are more complex features. For a more complete description of ice ridges refer to *Ice Ridge Characteristics and Engineering Concerns Regarding Ice Ridge*. Characteristics needed include total thickness (sail plus keel), thickness of refrozen part of ridge (consolidated layer), ridge width and length, thickness of level ice in which the ridge is embedded, and drift speed. Again, at least likely maximum values and ideally distributions are needed.
- Ice accretion; ice accretion on structures due to tidal action or splash can change the geometry of a structure and also add weight to it.

These characteristics may apply to river or lake ice as well as sea ice, whether first-year or multi-year.

3.2. Structure Geometry

Structure geometry itself affects the interaction scenarios, and has to be taken into consideration. Structure types include:

- Vertical mono-structure; a single monolithic structure may be wide or narrow, either in absolute terms or in relation to the ice thickness. The ratio of structure width to ice thickness is termed aspect ratio and can be related to the likely mode of failure. If the width of the structure is say less than twice the ice thickness, the surrounding ice confines the ice and a three dimensional compressive stress state is created in front of the structure and high ice pressures result. As the structure gets wider in relation to the ice thickness, other failure modes of flexure and buckling are more likely to arise and the effective ice pressure decreases. Mono structures may be used in some cases because of simplicity of construction, sand or gravel fill of sheet pile walls for a dock, or a concrete caisson for storage of crude oil in an offshore structure.
- Multileg; this geometry reduces the total area exposed to ice loading. It is also expected that the leading leg or legs disturb the ice cover, reducing the ice loading that following legs encounter. On the other hand, ice rubble may jam between the legs or freeze to the legs, substantially increasing the area exposed to ice loading. Multi-leg structures are generally applied in areas where ice loading is not severe. Docks or jetties are often constructed of multiple piles, supporting a deck and berthing face. Bridges are also sometimes supported on multiple piles, rather than monolithic piers. Multi-leg structures have been used in the Sakhalin offshore to reduce wave loading while minimizing ice loads on the legs.
- Slope; sloping structures can be narrow or wide, and break ice upwards or downwards. The bending failure mode generally results in lower ice loads. The ice load will be the sum of the ice-breaking and ice-clearing forces. The ice-breaking forces are determined from analysis of the failure of a plate on an elastic foundation. An important parameter is the large-scale flexural strength of the ice, however there are limited data at the scale of such interactions. The ice-clearing forces are very

important and depend on temperature, buoyancy, gravity, rotation, friction, and inertial effects. Ice can freeze to the structure surface, inhibiting bending failure and increasing the ice load in subsequent interactions. Broken ice generally clears more easily around a narrow sloping structure than a wide one Sloping elements can be added to a vertical structure to promote flexural failure of the ice and as a result lower ice loads. Note that if the slope is close to the vertical a sloping structure no longer induces flexural failure and it has to be treated as a vertical structure.

- Water depth; the depth of water at the face of the structure can influence failure modes and loading scenarios. For shallow water depth, mobile thinner ice in the autumn can fail and build up a grounded rubble accumulation which isolates the structure from direct action of thicker ice later in the winter. A sub-sea berm can provide a barrier to thick ice features (floes) which can be slowed by grounding. The energy absorbed by deformation of the berm and uplift of the floe dissipate the floe's momentum and thereby reduce the potential force on the structure.
- Waterline shape; shape in plan view may have some influence on ice loads. In situations where a corner of a rectangular structure is oriented towards the preferred ice motion direction it can promote a splitting failure mode. Generally the shape of a structure at the waterline has a small influence; a round structure will see about a 10 - 15% smaller force than an equivalent-width square structure. For ice impact scenarios, the local shape of the structure can have a significant effect on the rate of energy dissipation in ice crushing (as will be discussed in Section 5.6), and thereby influence ice loading.

3.3. Limiting Mechanisms (Limit Stress, Limit Force, Limit Momentum)

Three limiting mechanisms to the ice forces have been recognized. They are generally termed limit-stress, limit-energy and limit-force, and it is important to recognize and evaluate them in order to come to a realistic estimate of ice forces.

- The first limiting mechanism is termed limit stress, the force associated with ice failing against the structure by whatever mode (crushing, bucking, bending, shear, etc.). For this mechanism to occur, there must be sufficient force acting on the ice feature for it to fail across the entire width of the structure. All possible ice velocities have to be considered. This mechanism generally results in the highest ice force.
- Another mechanism is limit-energy, where the kinetic energy or momentum of the ice feature, often augmented by the limit force, is dissipated by the ice failing against the structure, coming to a complete stop. The maximum ice force during the event is determined and compared with the limit stress ice force. Velocity and mass of the ice feature, and relative shape of the edge of the ice feature and the structure are key factors in this mechanism. If sufficiently low limits of ice velocity or mass can be established, limit energies force may be less than the limit stress force.
- For the limit-force mechanism, the actions of winds, currents and the surrounding pack ice on an ice feature in contact with the structure may not be sufficient to fail the ice across the whole width of the structure. Application of this limiting mechanism requires knowledge of wind and current drag on the ice feature, its size and importantly pack ice forces on it.

It can be seen that application of these limiting mechanism for ice forces requires considerable knowledge of ice properties, ice conditions, and environmental factors. All three mechanisms must be assessed and the one giving the lowest force controls.

3.4. Failure Modes

The mode by which ice fails against the structure plays a key role in the magnitude of the ice force. The failure mode of ice, be it crushing, flexure, shear, splitting, buckling or creep, depends on ice factors (thickness, ice strength, ice velocity, ice temperature) and structure shape. Failure modes provide a qualitative description of the manners observed when ice fails against a structure. It is from these modes that models are developed from which ice forces can be calculated.

- Creep; failure mode which occurs when the ice is deforming at such slow strain rates that little or no micro-cracking occurs, and there are no large fractures in the ice. The strain rates relating to creep are typically 10^{-5} s^{-1} or lower. Normally creep is not the failure mode which results in the highest ice loads, but in certain cases where ice movement rates are slow and limited, it may be the controlling failure mode.
- Bending; failure associated with out of plane deformation of an ice sheet producing bending and generally occurs because of a sloping structure, but it may also be induced by ice overrunning ice rubble accumulations. The breaking length may be a few times the ice thickness. The forces to fail an ice sheet in bending are generally lower than those in crushing.
- Buckling; an instability failure mode, which occurs more readily if combined with some sort of eccentric load. Thin ice sheets are more susceptible to buckling failure. Buckling does not necessarily involve any fracture of an ice sheet, but after buckling, bending failure and fractures of the ice sheet may occur.
- Splitting; a high local stress state at the interface between the ice feature and structure which has a tensile component and causes single or multiple vertical macro-fractures to propagate.
- Crushing; a compressive failure mode of multiple micro- and macro-cracking, producing a disaggregated collection of ice fragments. Ice force may be relatively continuous or intermittent. Depending upon rate, which will be discussed later in this Chapter it has been termed brittle crushing at velocities greater than 10 to 100 mm/s, and ductile crushing or intermittent crushing at lower velocities.
- Spalling; failure involves planar cracks running from the contact interface out to a free surface at the top or bottom of the ice cover. A spall removes a relatively large volume of ice from interaction zone, requiring a relative small force to move it out of the way. A spall formation is associated with a relatively large drop in ice force.

Before proceeding to methods for calculating ice forces, mechanical properties, an indirect, but very important factor in defining ice forces, will be discussed.

4. Physical and Mechanical Properties of Ice

Ice is a material that is very close to its melting point in the temperature range in which it is normally encountered in nature. Ice can creep under low applied stress and at high temperature, or it can fracture in a brittle fashion under rapid loading. There are two primary ways to categorize ice. One is based on its origin: freezing of fresh water or sea water or compaction of snow in glaciers. The other is based on its form: level uniform ice sheet, large ice floes, or accumulations of broken ice pieces in ridges or rubble. The conditions under which ice forms will determine its grain structure; the common forms are frazil ice, columnar ice, discontinuous columnar ice, and granular ice. The porosity of the ice due to the presence of air or brine, and the grain structure, significantly influence the mechanical properties of the ice.

4.1. Physical Properties

The physical properties of ice help define and explain certain mechanical properties. An understanding and appreciation of them provides insights into ice mechanical properties and ice loads.

4.1.1. Grain Structure

Development of an ice cover typically starts with the formation of a surface skin of randomly oriented grains, originating either from crystals nucleating in the water or snow falling onto the surface. In response to one-dimensional heat conduction through the ice to the top surface, elongated columnar grains grow with their long axes normal to the surface. These columnar grains normally have their crystallographic symmetry axes randomly oriented in the horizontal plane. Grain structure influences the strength of ice. The growth and properties of ice are described in detail in *Lake Ice*.

4.1.2. Temperature

The temperature of an ice cover is characterized by a gradient, generally colder at the top surface and at the freezing point at the bottom surface. Snow on the surface insulates the ice sheet from the direct influence of air temperature. Colder ice is stronger and more brittle than warmer ice.

4.1.3. Salinity

When sea water freezes a certain amount of brine is incorporated into the ice, typically 35 ppt sea water will result in sea ice with an average bulk salinity of about 6 ppt. Sea ice is not a homogeneous alloy of ice and salts. The ice crystal lattice rejects impurities, so the saline brine remains as a high salinity liquid confined to small elongated pockets distributed throughout the ice. The result is that sea ice has a porous structure composed of solid ice and liquid brine pockets, for which the porosity is dependent upon the salinity and temperature of the ice. The porosity is termed brine volume by the sea ice community. For warm sea ice approaching -2°C, the porosity or brine volume may approach 25%. On the other hand, as the ice gets colder the size of these pockets becomes much smaller and the porosity may decrease to 1% at -20°C. An equation for relating brine volume to salinity and temperature will be presented later in Section 4.2.2.

4.1.4. Density

The density of pure ice is 917 kg/m^3, but the presence of air bubbles can reduce it to 800 kg/m^3 or even lower. The presence of salt or brine in sea ice allows for pores in the ice to be filled with brine and results in higher bulk densities of 920 or 930 kg/m^3. Density is an important property when calculating forces due to ridge interaction with structures since terms including the difference in density between ice and water play a key role.

4.2. Mechanical Properties

The primary mechanical properties used, even if indirectly, in ice load calculations include, strength, modulus of elasticity, and friction and adhesion. Strength and modulus are related to ice alone, whereas friction and adhesion are interface properties involving both ice and the material with which the ice is interacting. There is a large literature on mechanical properties, so only a high level overview is given here.

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Biographical Sketches

Robert Frederking, part time Principal Research Engineer at the National Research Council of Canada, Ottawa. He has a B.Sc. in Mechanical Engineering from the University of Alberta 1964, M.Sc. in Applied Mechanics from the University of London 1966, and Ph.D. in Applied Mechanics from the University of Illinois 1968. After 2 years at the Defence Research Board he joined the National Research Council to work on ice engineering problems. This included laboratory and field work on mechanical properties of ice, ice cover characterization and ice forces on structures. He has led three major field projects to the high Arctic that carried out measurements of ice indentation pressures. They were relatively large-scale measurements and the results contributed to specifying the ice pressures used in the design of gravity and floating structures off the East Coast of Canada, revisions of the Canadian Arctic Shipping Pollution Prevention Regulations and ISO 19906Arctic offshore structures. He was a Scientific Editor for the Journal of Glaciology, Editor in Chief of the Journal of Cold Regions Science and Technology, is currently an editor of the Journal of Offshore and Polar Engineering. He is the Chair of the Canadian Advisory Committee to ISO/TC67/SC7 Offshore structures.

Dr. Karl Shkhinek is the scientist emeritus of the Russian Federation, Professor of the Saint Petersburg State Polytechnical University (SPbSPU, Russia). He graduated as Research Engineer in Ships Hydromechanics and Strength from the Leningrad Shipbuilding Institute in 1956; defended the Candidate Degree Thesis in1961 and the Doctoral Degree Thesis (at the Institute of Physics of the Earth of the USSR Academy of Science) in 1973. For a long time he worked in hydromechanics, mechanics of solid body, and seismology. Dr. Shkhinek was the Head of the laboratory of structures' dynamics. In 1984 he became Professor at the SPbSPU. The main courses, he is in charge of, are Offshore Structures, Loads and Actions on Structures, Reliability of Structures. Dr.Shkhinek was co-supervisor in INTAS grant for Offshore Structures in 1993-95 and 1998-2000. He participated in the EC project LOLEIF, in preparation of the Russian code SNiP 1995 and ISO 19906. He is the author and co-author of 7 books, 23 inventions, and number of papers.