Cold Regions Science and Technology 95 (2013) 53–66

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Revisiting the Sanderson pressure–area curve: Defining parameters that influence ice pressure

G.W. Timco *, D. Sudom

National Research Council of Canada Ottawa, ON K1A 0R6, Canada

ARTICLE INFO

Article history:
Received 11 October 2012
Accepted 8 August 2013

Keywords:
Sea ice
Pressure
Loads
Design
Offshore
Structures

ABSTRACT

There is a strong perception in the ice mechanics community that during ice–structure interaction, the ice pressure always decreases as the area of contact increases. This understanding is often based on the pressure–area plot published by Sanderson (1988), which combines a large number of data sources and ice interaction situations on a single plot and shows a definite decrease in pressure with increasing area. This paper examines the data sources in the Sanderson plot as well as some more recent data, and discusses the definitions of global, local, spatial and process pressure–area. It is found that the pressure over a defined local geometric area or over the full global ice contact area can either show no dependence on area or a decrease with increasing area, depending on the interaction scenario. Factors other than area are examined to determine their influence on pressure including the loading rate, aspect ratio, ice failure mode, and ice properties. It is shown that in many cases, these factors are more important than the area in predicting ice pressure. The theory of Palmer et al. (2009) provides a reasonable explanation for some of the observed trends in pressure–area behavior. Examples from field data are provided to illustrate the application of pressure–area relationships for offshore structures in icy waters.

1. Introduction

The pressure exerted by ice is an important factor for the design and operation of ships, petroleum-related platforms or any other offshore structures in ice-infested waters. In 1988, Tim Sanderson presented a plot of data from laboratory strength and indentation tests, impact hammers, offshore platforms, and meso-scale models (Sanderson, 1988). The plot, shown in Fig. 1, shows a definite trend of decreasing pressure with increasing area. This fact has been become a key element of ice mechanics and it is basically viewed as strictly correct. But is it?

The authors have heard on countless occasions, mainly from those people who have limited knowledge in ice mechanics (or are new to the field) that "…according to the Sanderson pressure–area curve, the pressure must be lower because the area is larger…". This paper will examine this type of thinking in detail.

The lead author of this paper spoke with Tim Sanderson about his plot when he first published it, raising the concern that it includes all types of essentially non-related data and thus could be presenting a false picture. Sanderson well understood the limitations of the plot and replied "I do not apologize for this plot. I realize that there are many unrelated data sets and that it is, in essence, a simple straightforward plot of data. It should be treated as such". The Sanderson pressure–area curve has become a cornerstone in ice mechanics and is used in design. But there is more to the pressure–area effect for ice than can be gleaned from one plot. This paper will examine the Sanderson curve and address two basic questions regarding ice pressure–area relationships:

- First, what is meant by pressure–area and what does the Sanderson plot say about this?
- Second, what other factors come into play in pressure–area relationships, and how are these treated in the Sanderson pressure–area plot?

1.1. Definition of pressure–area

The most fundamental question to ask is: "What do we mean by pressure–area?". There are in fact several definitions used to describe ice pressure and area and they are summarized in this section.

1.2. Global and local pressure–area

Global pressure is related to the global (or nominal) area, which is defined as the contact area that develops during the interaction. This is simply the area of the structure projected onto the dimensions of the ice feature at the appropriate amount of penetration. The size of this area could be small (e.g., laboratory tests), intermediate, or large (e.g., interaction of an ice sheet with an offshore structure). Global pressures are generally thought of with respect to overall structure design and stability.

Local pressure occurs over a smaller, defined portion of a larger global area. For example, a local pressure could be captured on one instrumented pressure panel on the side of a large offshore structure. In this case the pressure is generally calculated using the maximum ice load

---

* Corresponding author. Tel.: +1 613 993 6673; fax: +1 613 952 7679.
E-mail address: garry.timco@nrc.gc.ca (G.W. Timco).

0165-232X/$ – see front matter. Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2013.08.005

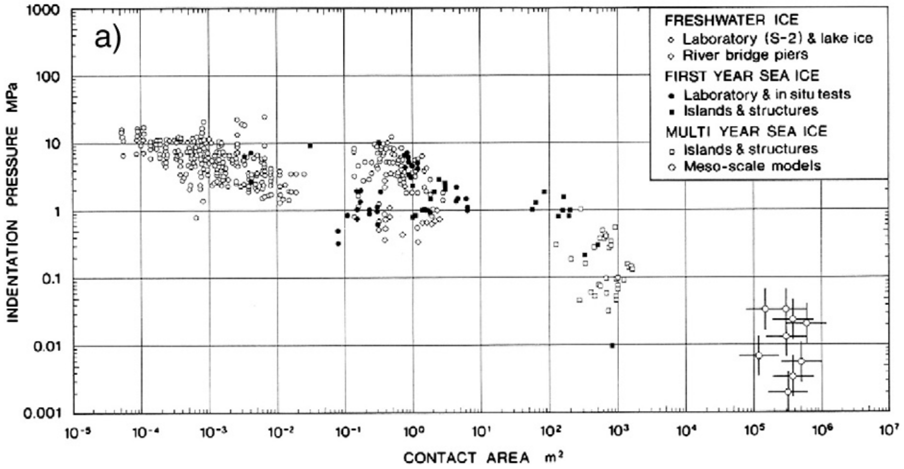

Fig. 1. Indentation pressure versus contact area.
From Sanderson (1988)

on the local measurement area during an event and the assumed corresponding *local* contact area. The local pressure is related to a part of the area of a structure to be designed; for example a panel or the plating between frames (Jordaan et al., 2005). Because the area is inside a larger area of ice, its confinement conditions can be quite different than that for the global pressure.

Fig. 2 shows the definitions used for global and local pressures in this paper, using the example of a cylindrical structure. The global interaction area corresponds to the full area over which the ice exerts a force on a structure at a given moment in time during the process of a pressure–area interaction. The role of High Pressure Zones will be discussed later in this paper.

Palmer et al. (2009) have discussed the pressure–area curve using a fracture mechanics approach. They make the distinction between the area over which a force is measured and the area that controls the force. Fig. 3 (from Palmer et al., 2009) shows a view perpendicular to an ice surface occupying region S (global surface area), limited by the continuous line. Force between the ice and a structure is measured over a smaller area M (measurement) defined by the dashed line. The force on M may not be determined by M alone (or by other properties of M such as its breadth or shape), but may depend on some different and perhaps larger area D (dependence), defined by the dotted outline, or indeed on the total global area S. They argue that pressure–area relationships in the past have tacitly assumed that S and M are coterminous and that this is an idealization and a source of disagreement on the subject. This is a key point in understanding the pressure–area effect. Using the definition of a local area does not give insight into the full interaction process.

In spite of this, the local pressure–area approach gives useful information on pressures measured over specific areas. Masterson and Frederking (1993) compiled a large number of pressure–area points based on small and medium scale experiments, icebreaker impacts with ice, and larger scale ice interactions with structures. In their analysis, local pressures were combined with global pressures measured over a smaller area. This combined data shows decreasing pressure with area with a functional form $p = 8.1\ A^{-0.572}$ for areas up to 19 m^2, where p is the pressure (in MPa) and A is the area in m^2. Above 19 m^2, the pressure appears constant at $p = 1.5$ MPa. Masterson et al. (2007) combined data from the MEDOF panels on the Molikpaq offshore platform, medium-scale field indentor tests and some flatjack tests to produce a combined pressure–area plot for local pressures. This data also showed a definite trend of deceasing pressure with increasing area, as shown in Fig. 4. Note that in contrast to the Masterson and Frederking (1993) plot, the Masterson et al. (2007) plot does not contain any data on ships in ice or global pressure–area data. The resulting upper bound pressure–area

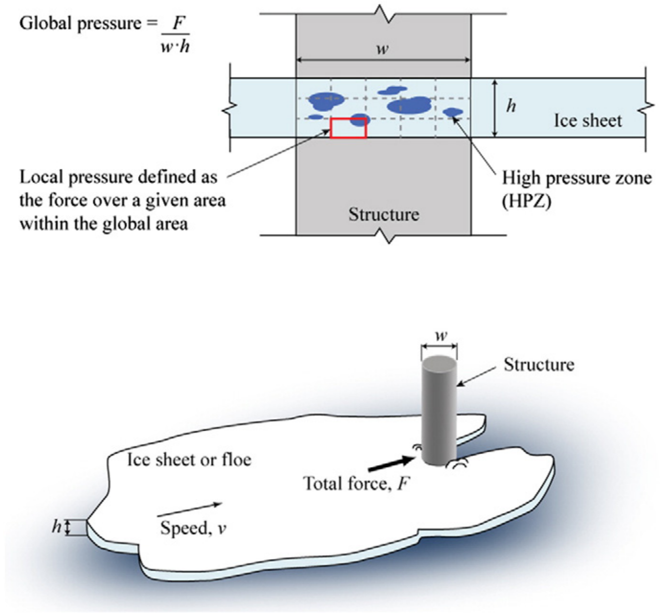

Fig. 2. Illustration of the definitions of global and local pressures used in this paper.

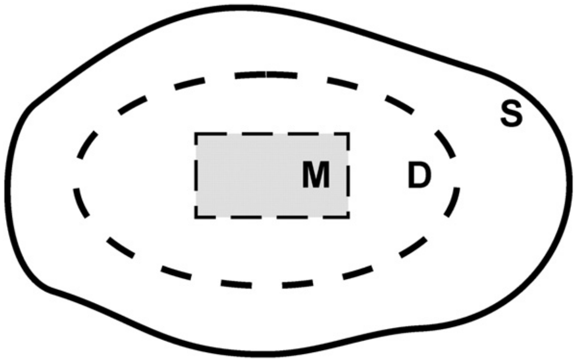

Fig. 3. Schematic illustration of the definitions used by Palmer et al. (2009).