Uncertainty and variation in measured ice-induced loads on a ship hull

Mikko Suominen
Uncertainty and variation in measured ice-induced loads on a ship hull

Mikko Suominen

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall 216 of the school on 27th of April 2018 at 12.

Cover photo taken by Niklas Kullström

Aalto University
School of Engineering
Department of Mechanical Engineering
Marine Technology
Supervising professor
Professor Pentti Kujala, Aalto University, Finland

Thesis advisors
Professor Jani Romanoff, Aalto University, Finland
Professor Heikki Remes, Aalto University, Finland

Preliminary examiners
Professor Jonas Ringsberg, Chalmers University of Technology, Sweden
Professor Rocky Taylor, Memorial University, Canada

Opponent
Professor Claude Daley, Memorial University, Canada
Abstract

Retreating Arctic sea ice offers new opportunities to harvest natural resources and opens up new shipping routes. In order to secure the safety of maritime operations, knowledge of ice-induced loads is needed. However, the ice-breaking process is a complex one. Full-scale measurements offer an opportunity to study the ice-induced loads on a ship hull as all the complexities are embedded in the measurements. The measurements are commonly conducted by measuring strains and the loading is determined from the load-strain relation. Thus, full-scale measurements contain additional uncertainty and variation related to the measurement techniques. Although the measurement uncertainty is an important topic, it has not received a noteworthy attention in earlier publications. The aim of this dissertation is to study the uncertainty and variation in the measured loading on the ship hull related to the load length. The focus is placed on the ice load measurements based on the shear strain difference.

In this study, an analytical grillage model is derived to determine the shear force and torsion on the ice-loaded and adjacent unloaded frames. The model is validated with a Finite Element Model and a calibration pull. The model is applied to define the structural parameters affecting the load transfer between frames. Furthermore, the theoretical model is used to obtain a robust estimate of the possible error and uncertainty related to the load length and the extent of the instrumentation.

Full-scale experiments on board S.A. Agulhas II are carried out in the Baltic Sea with first-year sea ice and the load length distribution is retrieved from these measurements. In addition, the measurements show that the loading on a frame increases as a function of the external load length. Furthermore, it is shown experimentally and explained theoretically that the extension of the instrumentation does not affect the measurements when the loading is short. However, the uncertainty and variation in the measurements increases when the load length increases beyond the instrumented area as a result of the load transfer between the frames.

The effect of the load length on the mean value, standard deviation, and probability distribution of load amplitude on a frame is explained. Furthermore, the study shows that the linear-like increase of the mean values of the ice-induced load on a frame as a function of the standard deviations is a mathematical phenomenon rather than a physical one. The study shows that the shape of the probability density function for the ice-induced load on a frame is exponential-like for short loads and lognormal-like for longer loads. In a case where a single probability distribution is to be fitted to both short and long loads, Weibull distribution gives the best fit to the measurement data.

Keywords ice load, full-scale, ice load statistics, measurement uncertainty, shear strain measurement
Tekijä
Miikko Suominen

Väittöskirjan nimi
Epävarmuus ja hajonta laivan rungolta mitatuissa jääkuormissa

Julkaisija
Insinöörirakenteiden korkeakoulu

Yksikkö
Konepohjoinen laitos

Sarja
Aalto University publication series DOCTORAL DISSERTATIONS 70/2018

Tutkimusala
Laiva- ja Meriteknikka

Kieli
Englanti

Monografia
Artikkeliväittöskirja
Esseeväittöskirja

Tiivistelmä


Avainsanat
jääkuorma, täysmittakaava, jääkuormien tilastollisuus, mitauspitauksia, leikkausvennämittaus

ISBN (painettu) 978-952-60-7943-1
ISBN (pdf) 978-952-60-7944-8

ISSN-L 1799-4934

ISSN (painettu) 1799-4934
ISSN (pdf) 1799-4942

Julkaisupaikka
Helsinki

Painopaikka
Helsinki

Vuosi
2018

Sivumäärä
142

The work was funded by the Finnish Funding Agency for Technology and Innovation (Tekes), the Academy of Finland, and the Lloyd’s Register Foundation (LRF). The Lloyd’s Register Foundation supports the advancement of engineering-related education and funds research and development that enhances the safety of life at sea, on land, and in the air. Their financial support is gratefully acknowledged. In addition, the University of Oulu, University of Stellenbosch, Aker Arctic, DNV-GL, Rolls-Royce, STX Finland, Wärtsilä, and the Department of Environmental Affairs (South Africa), as partners of the Tekes project NB1369 Full-scale ice trial, the Finnish Meteorological Institute, as a partner of the Academy of Finland project ANTLOAD, Lappeenranta University of Technology, as a partner of the Academy of Finland project WINICE, and Memorial University, the Norwegian University of Science and Technology, the Technical University of Hamburg-Harburg, and the University of Helsinki, as partners of the LRF’s project CEARCTIC, are gratefully acknowledged. I would also like to acknowledge LightStructures for instrumenting S.A. Agulhas II and helping with the practicalities of the instrumentation.

Most of all, I would like to thank Professor Pentti Kujala for the guidance and all the work and time dedicated to this thesis. You always found time and helped me when I needed it. I am grateful to you for your attitude towards fieldwork and full-scale measurements and the opportunity to conduct them. During the preparation of this thesis, I spent seven months on ice fields or on board vessels in the Arctic, Antarctic, and the Baltic Sea, which is a rare opportunity. I would also like to thank Professor Jani Romanoff for the work and the time you spent on guiding this work and in coaching me. Many of the discussions led me to process the big picture and also the small details. You pointed out the unclear parts and highlighted the importance of the details, which improved the quality of the papers a lot. I am also grateful to Professor Heikki Remes for his support for this thesis and giving an outside view on the papers. This helped me clarify and focus the papers. I would like to thank the pre-examiners Professor Jonas Ringsberg and Professor Rocky Taylor for the examination and valuable comments. The comments helped to improve the manuscript by pointing out the parts that should be improved and parts that were absent. Besides the professors, I would like to acknowledge Håkan Enlund from Rauma Marine Constructions for his initiative to instrument S.A. Agulhas II. The instrumentation led to the research which formed a major part of this thesis, four papers out of five. I would also like to thank Jani Hoikkala for his effort in planning and realizing the measurements and practical help during the instrumentation.

I started as a student at Helsinki University of Technology (HUT, part of Aalto since 2010) in 2005 and as a staff member at HUT in 2008. These years have taken me around the Nordic countries and Northern Europe as a student thanks to Laivanrakentajain kerho (the Shipbuilders’ Club at HUT/Aalto). Working on measurements on board different vessels and on ice
fields, research projects with different academies and companies, and conferences have taken me around the globe. Besides student and work life, I have spent a lot of time doing sports. Within these activities, I have gained many good friends and colleagues. You have inspired me and given me thoughts and ideas that contributed to the work, and also something else to think about, and encouraged me in different ways. I would like to thank you all for these. I will not name individuals as there are so many of you that I would inevitably forget to list someone.

I am also deeply grateful to my brother and, especially, to my mother for supporting me through my life. I know that I can always count on you. Finally, I would like to thank my wife Paulina for always being supportive and cheering me up when I needed it.

Espoo, 29 March 2018
Mikko Suominen
Contents

Acknowledgements ........................................................................................................... 1
List of Publications ......................................................................................................... 5
Author’s Contribution ..................................................................................................... 6
Original features ............................................................................................................. 7
List of Abbreviations and Symbols .............................................................................. 9

1. Introduction ................................................................................................................. 13
   1.1 Background and motivation ................................................................................. 13
       1.1.1 Requirements for the design ...................................................................... 13
       1.1.2 Variations in operational and ice conditions and their effect on the load magnitude ........................................................................................................... 14
       1.1.3 Ship-ice interaction .................................................................................... 16
       1.1.4 Methods to study the loads in the structure-ice contact ... 18
   1.2 Earlier full-scale studies ..................................................................................... 19
       1.2.1 Full-scale instrumentations ...................................................................... 19
       1.2.2 Challenges and uncertainty in shear strain measurements ...................... 22
   1.3 Objectives of the work ....................................................................................... 23
   1.4 Limitations .......................................................................................................... 25

2. Structural ability to transfer loading ......................................................................... 27
   2.1 Structural response ......................................................................................... 27
   2.2 Effect of structural parameters on load transfer .............................................. 28
   2.3 Shear strain measurements ............................................................................. 30

3. The extension of the instrumentation ...................................................................... 33
   3.1 The background of load amplitude as a function of load length ...................... 33
   3.2 The uncertainty in the measurements related to the load length .................... 34
   3.3 Description of the applied full-scale measurement applied ... 34
       3.3.1 The instrumentation of S.A. Agulhas II and data processing ................. 34
3.3.2 The measurement voyage and data processing of the measurements.......................................................... 38

3.4 Load length distribution and variation in the determined loading resulting from the extension of the instrumentation 40

4. The load length distribution and the load amplitude probability distribution on the frame .............................................................. 45

4.1 Variation in short-term ice-induced load amplitudes on a ship hull and related probability distributions 45

4.2 Variation in the statistical parameters resulting from the extension of the instrumentation 47

4.3 The effect of the load length on the amplitude probability distribution 48

5. Conclusions ................................................................................. 51

5.1 Summary of main findings ...................................................... 51

5.2 Recommendation for full-scale instrumentations .................. 52

5.3 Future work ............................................................................. 54

References........................................................................................................ 57
List of Publications

This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their Roman numerals


II. Suominen, Mikko; Romanoff, Jani; Remes, Heikki; Kujala, Pentti. The determination of ice-induced loads on the ship hull from the shear strain measurements. Analysis and Design of Marine Structures - Proceedings of the 5th Int. Conf. on Marine Structures, Southampton, UK, March 25-27, 2015.


IV. Suominen, Mikko; Karhunen, Jouko; Bekker, Anriëtte; Kujala, Pentti; Elo, Mikko; von Bock und Polach, Rüdiger; Enlund, Håkan; Saarinen, Sami. Full scale measurements on board PSRV S.A. Agulhas II in the Baltic Sea. Proceedings of the 22nd Int. Conf. on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland, June 9-13, 2013.

Author’s Contribution

**Publication I: Influence of load length on short-term ice load statistics in full-scale**

The author analyzed the full-scale measurements, developed the analytical grillage model, and wrote the manuscript. Kujala, Romanoff, and Remes contributed to the work with valuable comments and suggestions.

**Publication II: The determination of ice-induced loads on the ship hull from the shear strain measurements**

The author conducted the research and wrote the manuscript. Romanoff, Remes, and Kujala contributed to the work with valuable comments and suggestions.

**Publication III: The Effect of the Extension of the Instrumentation on the Measured Ice-Induced Load on a Ship Hull**

The author re-analyzed the full-scale measurements and wrote the manuscript. Kujala, Romanoff, and Remes contributed to the work with valuable comments and suggestions.

**Publication IV: Full scale measurements on board PSRV S.A. Agulhas II in the Baltic Sea**

The author planned, conducted, and analyzed the ice-induced load measurements and wrote a major part of the manuscript. Karhunen, Bekker, Elo, Saarinen, and von Bock und Polach planned, conducted, analyzed, and wrote the sections concerning shaft line, human comfort, mechanical property, and ridge profiling measurements, respectively. Kujala and Enlund contributed to the manuscript with valuable comments and suggestions.

**Publication V: Variation in short-term ice-induced load amplitudes on a ship's hull and related probability distributions**

The author processed and analyzed the data and wrote the manuscript. Kujala formulated the topic and contributed to the work with valuable comments and suggestions.
The aim of this thesis is to study the uncertainty and variation present in the ice-induced loads measured in full-scale. The thesis focuses on the measurements based on the shear-strain difference. The aim is to clarify the variation that originates from the scatter on the actual load length. The following features of this thesis are believed to be original.

1. An analytical grillage model is derived to determine the shear force and torsion on the ice-loaded and adjacent unloaded frames [PI, PII]. This allows the identification of the load-length from the measured shear strains. The structural parameters affecting the load transfer between frames are determined analytically [PI, PII]. The model explains how instrumentation on the different sides of the frames reduces the possible error in the load amplitude determination [PI]. The theoretical models are used to obtain a robust estimate of the possible error and uncertainty related to the load length and the extent of the instrumentation [PI, PIII].

2. The analytical grillage model is validated numerically with the Finite Element Method (FEM) and experimentally by calibration pull of a ship structure exposed to an experimental campaign in full-scale [PI-PIV]. Full-scale experiments are carried out in the Baltic Sea with first-year sea ice [PIV]. The load length distribution based on full-scale measurements is presented for first-year sea ice in the Baltic Sea [PI, PIII]. It is observed that the loading on a frame increases as a function of the external load length in the full-scale measurements [PI].

3. It is shown experimentally and explained theoretically that the extension of the instrumentation does not affect the measurements when the loading is short [PI, PIII]. The uncertainty and variation in the measurements is observed to increase when the load length increases beyond the instrumented area as a result of the load transfer between the frames [PI-III].

4. The linear-like increase in the mean values of the ice-induced loads on a frame as a function of the standard deviations is observed. This is a mathematical phenomenon rather than physical one [PV]. This is a result of the mathematical definitions of the mean value and standard deviation and assuming the smallest measured loads form the initial sample set that is the same for all the periods and the maximum of the period is a unique value for each set.

5. The effect of the load length on the mean value, standard deviation, and probability distribution of the load amplitude on a frame is presented for short-term ice-induced loads [PI, PIII]. It is observed that the shape of the probability density function for the ice-induced load on a frame is exponential-like for short loads and lognormal-like for longer loads [PI]. In a case where a single probability distribution is to be fitted to both
short and long loads, Weibull distribution gives the best fit to the measurement data [PI].
List of Abbreviations and Symbols

a  Influence coefficient matrix
b  Inverse of the influence coefficient matrix
c  The coefficient in FSICR for the probability that the full length of the area under consideration will be under loading
d  Stiffness of the plate
e  Young's modulus
fE  The probability density function of exponential distribution
fLN  The probability density function of lognormal distribution
fW  The probability density function of Weibull distribution
F  Load
Fc  Contact force
Fc,z  The horizontal component of the contact force
Fc,x  The vertical component of the contact force
FEXT  External load
hc  Contact height
hi  Ice thickness
i, j  The number of a frame
IF  The second moment of inertia of a frame
My  Bending moment affecting the frame
m  Total number of frames
L  Frame length
Qi  Shear force on a frame i
QFrame  Shear force on the loaded frame
s  Frame spacing
Ti  Torsion on a frame i
\( w_i \)  Deflection of a frame \( i \)
\( x, y, z \)  Local coordinates
\( X, Y, Z \)  Global coordinates

\( \beta_n \)  Frame angle
\( \beta_W \)  The shape parameter of Weibull probability distribution
\( \Delta \)  Difference
\( \theta_i \)  Rotation of a frame \( i \)
\( \gamma_i \)  Shear strain on a frame \( i \)
\( \gamma_l \)  The location parameter for the probability distribution
\( \lambda_E \)  The rate parameter of the exponential probability distribution
\( \mu \)  Mean value
\( \mu_{LN} \)  The location parameter of the lognormal probability distribution
\( \eta_W \)  The scale parameter of Weibull probability distribution
\( \sigma \)  Standard deviation
\( \sigma_{LN} \)  The scale parameter of the lognormal probability distribution

bpp.  Between perpendiculars
CANMAR  Canadian marine drilling
CCGS  Canadian Coast Guard Ship
CoV  Coefficient of variation
FE  Finite Element
FEM  Finite Element Model
FEA  Finite Element Analysis
FS  Frame spacing
FSICR  Finnish-Swedish Ice Class Rules
IACS  International Association of Classification Societies
IB  Icebreaker
KV  Kystvakt (Norwegian)
MS  Motor Ship
MT  Motor Tanker
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>Patrol Vessel Medium</td>
</tr>
<tr>
<td>PSRV</td>
<td>Polar Supply and Research Vessel</td>
</tr>
<tr>
<td>PV</td>
<td>Patrol Vessel</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene difluoride</td>
</tr>
<tr>
<td>RV</td>
<td>Research Vessel</td>
</tr>
<tr>
<td>UR</td>
<td>Unified Requirements</td>
</tr>
<tr>
<td>USCGC</td>
<td>United States Coast Guard Cutter</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Background and motivation

1.1.1 Requirements for the design

Because of the retreating sea ice in the Arctic, new shipping routes and natural resources have become available. Maritime operations in the Polar Regions and in ice-infested waters have created a need to develop different types of ice-capable vessels, e.g. tankers, supply vessels, and icebreakers, for different operations and ice conditions. In order to protect lives at sea and the environment, the safety of the structure has to be considered in the design. The consideration of the safety is a topic with two aspects. It requires knowledge of the structural response (the limit states of the structure and load-carrying capacity), and the magnitude and frequency of external loads. When the load-carrying capacity of the structure and the external loads are known, a safety factor can be determined.

The structural response (limit states) and load definition are considered when the design points for given probability levels in the ice class rules are defined. The limit states for an ice frame can be coarsely divided into elastic, plastic, and ultimate limit states (Riska and Kämäräinen, 2012). The division is considered coarse, as the plastic and ultimate limit states are not unambiguous, especially for frames, as different definitions can be given for these states (Riska and Kämäräinen, 2012; Daley et al., 2001). The rules employ different design criteria. The Unified Requirements (UR) of the International Association of Classification Societies (IACS) consider plastic design criteria, where the framing requirement is based on an idealized plastic collapse onset mechanism derived with the energy methods (Daley et al., 2001; Daley, 2002; IACS, 2016). Because of the simplifications, the beneficial effects of the membrane stresses and strain hardening are not accounted for. Thus, the structure does not collapse when the design load is reached, but has a substantial reserve (Daley et al., 2001; Kõrgesaar et al., 2018).

Unlike the IACS, the Finnish-Swedish Ice Class Rules (FSICR) apply elastic design criteria (i.e. a yield limit state is applied). Thus, the definition for the required structure is simplified. However, the design philosophy in the FSICR is such that the yield limit state is reached once in a winter and the plastic limit state once in a ship’s lifetime, which has been confirmed by comparing the structural load-carrying capacity to the full-scale measurements (Riska and Kämäräinen, 2012). Thus, although the structural definition is gained through elastic formulations, the higher load-carrying capacity is embedded in the rules. As the FSICR have long traditions, the rules have been fine-tuned over the years and the feedback from the develop-
ment of the rules has been gained through full-scale measurements, damage studies, and observing the merchant vessels visiting Finnish and Swedish ports regularly (Riska and Kämäräinen, 2012).

Although the load-carrying capacity of the structure is an important topic, it is related to the ultimate strength analysis of the structures. The ultimate strength analysis is a complex problem which requires research focusing purely on it. This work concentrates on the other important topic, i.e. the magnitude and occurrence of the ice-induced loads, and the ultimate strength is left for future studies.

1.1.2 Variations in operational and ice conditions and their effect on the load magnitude

The ice-induced loads are closely related to the ice-breaking process in which the ship moves in relation to the ice. However, ice-breaking is a complex process, as it involves different levels of mechanical processes; see Figure 1. These mechanical processes involve a variety of ice conditions, ship operations, and structural responses, which can be used to describe the different levels of statistical processes; see Figure 1. In essence, this process is random and the ice-induced load on the ship hull varies significantly even in the short term; see Figure 2. Even though the process is random, in principle we can use probability theory to predict design ice loads statistically (Ochi, 1990; Jordaan, 2005). This can be done for a certain time interval, resulting in a short-term prediction. Series of short-term predictions can be used to derive long-term predictions.

Spatially, first-year ice conditions in a certain sea area vary locally from easy level ice to heavily deformed ice sheets; this is due to the dynamics of the ice field. Temporarily, at the beginning of the ice season, grease ice starts to form, which develops into thin new level ice or forms pancake ice as a result of wave interaction. Level ice and large floes can further increase the thickness through thermal growth or compression, depending on the weather conditions. In the case of compression, the ice deforms through rafting or forms compression ridges. At the location of the deformation, the thickness can increase rapidly through mechanical processes and be significantly greater than in the surrounding field (Strub-Klein and Sudom, 2012). The ice conditions around the ship determine the manoeuvrability of the ship. In the case of a loose floe field, the ship can push small floes aside. However, in a dense floe field, the floes interact with other floes, restricting the movements of the ship. Thus, the ship has to break and submerge the floes. Locally, the geometry and mechanical properties of the floes vary from a weak porous ice to a strong solid ice (Timco and Weeks, 2010), which further affects the breakage of the floes. As a result of these processes, the amplitudes of the ice-induced loads on the ship hull vary significantly; see Figure 2.
The parameters affecting the magnitude of the loading on the ship hull through the mechanical processes can be coarsely divided into parameters related to the ship operations and ice conditions. From the operational point of view, the effects of the speed and manoeuvrings have commonly been considered. The studies have shown that the turnings do not have a clear effect on the loads in the bow area, but increase the magnitude and the frequency of the ice-induced loads in the stern shoulder area; see e.g. Bekker et al. (2014); Suominen et al. (2015). Commonly, the speed is considered to have an increasing effect on the magnitude of the loading. However, measurements have shown that the effect is not clear as the highest loads have been measured at intermediate speeds on many occasions (see e.g. St. John and Minnick, 1995; Hänninen et al., 2001; Suominen et al., 2015).

When it comes to the ice condition parameters, the ice thickness is considered to be the most important parameter affecting the load magnitude. Several studies have shown that the ice thickness has an increasing effect on the ice load magnitude (see e.g. Hänninen et al., 2001; Suominen et al., 2015; Kotilainen et al., 2017). This is reasonable, as the thickness will increase the mass and bending stiffness of the ice floe and the possible contact area in the vertical direction. The ice thickness is also present on all the hierarchy levels of the mechanical processes presented in Figure 1. The studies have also suggested that the ice concentration would have
an increasing effect on the load magnitude (see e.g. Ritch, 2008; Suominen et al., 2015). This is also reasonable, as an increase in the concentration prevents ships from using open water leads, which increases the number of ice loads, i.e. the exposure. Furthermore, it affects the dynamics of the ice field, as the floes cannot move away from the ship’s path, but the ship has to break through. The effect of the floe size on the load magnitude has not been studied in detail, but it has an effect through the field-ship dynamics, as described above. The mechanical properties of the ice have a direct effect on the load level as stronger ice requires a higher load to be break it.

Although the mechanical processes have different hierarchy levels and different parameters affect the magnitude of the loading, the loads are transmitted to the hull through the ship-ice interaction.

1.1.3 Ship-ice interaction

At the beginning of the breaking process, the edge of the ice floe crushes against the hull. As a result, the contact area increases. This area has a normal in the direction opposite to the hull surface normal. This results in an increase in the total contact force, $F_c$. The failure mechanisms (bending, crushing, flaking, etc.) and loading required to break the ice are greatly affected by the location of the contact at the ship hull and the mechanics of the ship with respect to the ice sheet (Varsta, 1983). If the frame angle, $\beta$, at the contact location is larger than zero, the contact force can be decomposed into a horizontal and vertical component, $F_{c,x}$ and $F_{c,y}$; see Figure 3B. As the total force increases along with the contact area, the downward component of the force at the ice edge increases. When the bending moment or shear force exceeds the load-carrying capacity of the ice floe, the ice breaks. The breaking through bending moment forms a cusp pattern in the ice floe; see Figure 3A. If the frame angle is zero, i.e. the frame is vertical, the ice fails through crushing and shearing. In the shear-dominated failure, the contact area increases until flakes have been formed and broken off from the ice sheet; see Figure 3B. The broken pieces of ice are submerged or pushed aside if the surrounding ice field permits it. These breaking processes exert a pressure on the ship hull and are repeated as the ship reaches the edge of the unbroken ice. However, the contact location and shape can vary rapidly; see Figure 4. This makes the treatment a challenge as it is a combination of material science and structural mechanics.
The contact location in ship-ice interaction is defined in the vertical direction by the floating position of the ship and by the thickness of the ice floe. Although the contact height can reach the ice thickness in the vertical direction in a relatively slow and ductile crushing failure process (Sodhi, 2001), laboratory (Joensuu and Riska, 1989) and shipborne measurements (Riska et al., 1990) with a polyvinylidene difluoride (PVDF) film have shown that in first-year ice conditions the ice induces a line-like pressure pattern on the ship hull, with the high-pressure area being clearly narrower in the vertical direction than the thickness of the ice. The same phenomenon has been observed in several studies (see e.g. Sodhi, 2001; Taylor and Richard, 2014).

In the horizontal direction, the contact is limited by the size of the ice floe and the ice failure processes. However, the length can be significant in relation to the height. In addition, the
pressure has been shown to vary significantly in the horizontal direction, forming high- and low-pressure zones (see e.g. Sodhi, 2001; Taylor and Richard, 2014). When the indentation speed is reduced, i.e. the ice breaks in a ductile manner by crushing and compression, or the thickness of the ice is great, the contact in the vertical direction is not line-like, but contains high- and low-pressure zones that are similar to those found in the horizontal direction; see e.g. Jordaan (2001); Sodhi et al. (1998); Sodhi (2001). This is especially the case for transverse-framed side structures.

The variations in the contact height and length and variations in the sample sizes in the compressive and crushing experiments resulted in measurements with different contact area sizes. This led to observations of the pressure-area curve where the average pressure over the nominal area decreases as the area increases. This was first observed by Sanderson (1988) while studying the pressure on offshore structures. Since then, the curve has been revised for offshore structures (see e.g. Masterson et al., 2007) and also observed from ship-based studies (see e.g. Frederking, 1999; Taylor et al., 2010). What is notable is that the curve decreases exponentially. Thus, the pressure in high-pressure zones, i.e. small areas, is significantly higher than in low-pressure zones.

Thus, it can be concluded that the contact area, location, pressure distribution, and the failure mode of the ice are affected by the floe size, ice thickness, the mechanical properties of the ice, structure indentation speed, frame angle, and response of the structure. In addition, a scale effect is present. Because of the complexity and different scales of the processes, different methods are needed and have been applied to study the whole process and sub-processes of the ice breaking and loading on the hull.

1.1.4 Methods to study the loads in the structure-ice contact

Ice-induced loading and the corresponding structural response have been studied theoretically (for semi-empirical approaches see e.g. Su et al., 2011a, b and for discrete element and finite element simulations e.g. Paavilainen et al., 2013), with laboratory experiments (see e.g. Daley, 1991, for the ice-breaking process against a rigid structure and Kim and Quinton, 2016, for a flexible structure), and full-scale measurements (see the recent review by Ehlers et al., 2015 and Table 1). Numerical studies and simulations offer an opportunity to study the effect of the ice conditions and mechanics on ice-induced loading. However, the drawback of numerical studies and simulations is that they require assumptions about different features and measurements for the validation. Laboratory experiments offer an excellent opportunity to study the local structure-ice interaction. However, the size and the number of repetitions in experiments are limited. The advantage of full-scale measurements is that all the variations, e.g. in ice conditions and the ice-breaking process, are embedded in the measurements. For these reasons, knowledge of ice-induced loads on a ship hull has been gathered extensively through full-scale measurements; see Kheisin and Popov (1973), Kujala and Vuorio (1986), St. John et al. (1994), and Leira et al. (2009).

Commonly, the variation in the measurements is assumed to result from the variation in ice conditions and properties, the ice failure mechanism, and ship operations. However, in the case of full-scale measurements, additional variation in the measured loading arises from the measurement techniques that are applied. The understanding of the level of uncertainty in the measurements is important as this affects the safety factors that are required when the ultimate strength of the structure is defined in the design. Despite the importance, the uncertainty caused by the ice-induced load on ship hull measurement techniques in full-scale has not been
widely studied before now. Thus, this study focuses on the uncertainty and variation in the measured local ice-induced loads on the ship hull related to the measurement techniques and extension of the instrumentation.

1.2 Earlier full-scale studies

1.2.1 Full-scale instrumentations

Because of the long tradition of full-scale measurements, different approaches to measuring ice-induced loading have been developed. These can be roughly divided into two main categories; indirect structural strain measurements – see Table 1 – and direct measurements of the contact pressure or load – see Table 2. When the strain measurements are applied, the load is extracted on the basis of the known structural parameters, assumed load shape, and measured strain data. One method is to measure the shear strain difference between two locations on a frame. Another method is to measure the compressive strain on the frame normal to the shell. Attempts to determine the local loading by measuring the bending strain at the flange of the frame have also been made. Besides strain measurements, different approaches have been applied to determine the ice-induced pressure by using pressure gauges inside (Vuorio et al., 1979) and outside the hull (Glen and Blount, 1984), load sensors (Hoffmann, 1985), pressure panels (Riska et al., 1990), and optics (Gagnon, 2008). As the pressure in the interaction can be extremely high and mechanical wear is significant, external gauges to measure pressure have not lasted a long time; see e.g. the measurements by Riska et al. (1990) with a PVDF film. External structures and methods to measure the pressure pattern outside the hull that can withstand the pressure have also been developed (Gagnon, 2008). However, these types of solutions alter the stiffness of the structure, which affects the load-carrying mechanism of the hull structure and possibly also the load amplitude. Thus, the local loads have commonly been determined by measuring the structural response through strain measurements.

In the indirect method, the strains are measured from the frame and the external loading is determined from the load-strain relation of the built structure. Commonly, the relation is determined with finite element analysis. Figure 5 presents how the strains in the web of the frame change when moved away from the loading point. When shear strains are measured, the structure is instrumented at least two locations. The shear force, i.e. the ice-induced load, acting between the two locations equals the change in the shear force between the two locations. When the compressive strain normal to the hull structure, the z-direction, is measured, the idea is to measure the localized load affecting the structure. The strain in the z-direction decreases rapidly outside the contact area. Thus, with this approach, the loads that have a direct effect at the location of the strain gauge can be determined.
Table 1. Full-scale measurements based on the strain measurements. Partly modified from Kendrick and Daley (2011) and Ehlers et al. (2015).

<table>
<thead>
<tr>
<th>Vessel/Cruise</th>
<th>Location</th>
<th>Year</th>
<th>Strain Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB Urho</td>
<td>Baltic Sea</td>
<td>1976</td>
<td>Shear strain*</td>
<td>Varsta (1976)</td>
</tr>
<tr>
<td>MT Igrim</td>
<td>Baltic Sea</td>
<td>1978</td>
<td>Shear strain*</td>
<td>Korri and Varsta (1979)</td>
</tr>
<tr>
<td>IB Sisu</td>
<td>Baltic Sea</td>
<td>1978-85</td>
<td>Shear strain difference</td>
<td>Kujala and Vuorio (1986)</td>
</tr>
<tr>
<td>CANMAR Kigoriak</td>
<td>Arctic</td>
<td>1979</td>
<td>Shear strain**</td>
<td>Ghoneim and Keinonen (1983)</td>
</tr>
<tr>
<td>USCGC Polar Sea</td>
<td>Arctic, Antarctica</td>
<td>1982-84</td>
<td>Compressive strain normal to shell</td>
<td>St. John et al. (1984), Daley et al. (1990)</td>
</tr>
<tr>
<td>MS Arcturus</td>
<td>Baltic Sea</td>
<td>1983-88</td>
<td>Shear strain difference</td>
<td>Riska (1982)</td>
</tr>
<tr>
<td>RV Polarstern</td>
<td>Arctic</td>
<td>1984-85</td>
<td>Strain***</td>
<td>Müller and Payer (1987)</td>
</tr>
<tr>
<td>MT Kashira</td>
<td>Baltic Sea, Arctic</td>
<td>1984-90</td>
<td>Shear strain difference</td>
<td>Kujala (1984)</td>
</tr>
<tr>
<td>MS Kemira</td>
<td>Baltic Sea</td>
<td>1985-91</td>
<td>Shear strain difference</td>
<td>Kujala (1989), Muhonen (1992)</td>
</tr>
<tr>
<td>CCGS Louis S. St. Laurent</td>
<td>Arctic</td>
<td>1994-95</td>
<td>Shear strain difference</td>
<td>Ritch (2008)</td>
</tr>
<tr>
<td>MT Uikku</td>
<td>Arctic, Baltic Sea</td>
<td>1998, 2000-01, 03</td>
<td>Shear strain difference</td>
<td>Kotisalo and Kujala (1999c), Lensu (2002b)</td>
</tr>
<tr>
<td>PM Teshio</td>
<td>Sea of Okhotsk</td>
<td>1998-99</td>
<td>Shear strain difference</td>
<td>Uto et al. (2005)</td>
</tr>
<tr>
<td>USCGC Healy</td>
<td>Arctic</td>
<td>2000</td>
<td>Shear strain difference</td>
<td>Hänninen et al. (2001)</td>
</tr>
<tr>
<td>CCGS Terry Fox</td>
<td>Arctic</td>
<td>2001</td>
<td>Shear strain difference</td>
<td>Ralph et al. (2003), Ritch et al. (2008)</td>
</tr>
<tr>
<td>IB Otso</td>
<td>Baltic Sea</td>
<td>2005</td>
<td>Shear strain difference</td>
<td>Valkonen (2007)</td>
</tr>
<tr>
<td>KV Svalbard</td>
<td>Arctic</td>
<td>2007-08</td>
<td>Shear strain</td>
<td>Leira et al. (2009)</td>
</tr>
<tr>
<td>PSRV S.A. Agulhas II</td>
<td>Baltic Sea, Antarctica</td>
<td>2012-18</td>
<td>Shear strain difference</td>
<td>Suominen et al. [PIV]</td>
</tr>
</tbody>
</table>

* The instrumentation designed to measure stresses. Loading approximated from the measured stress distribution
** Large number of strain gauges mounted on the flange of frames as well
*** Not clear what strains were measured. On the basis of a figure, the compressive strains normal to the shell were measured.
Table 2. Full-scale local ice load measurements based on other than strain measurements.

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Location</th>
<th>Year</th>
<th>Measurement Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT Igrim, Baltic Sea, 1978</td>
<td>Special type of pressure gauge installed inside the hull.</td>
<td>Reference: Korri and Varsta (1979)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB Sisu, Baltic Sea, 1978-85</td>
<td>Special type of pressure gauge installed inside the hull.</td>
<td>Reference: Vuorio et al. (1979)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CANMAR Kigoriak, Arctic, 1979</td>
<td>Special type of pressure gauge installed inside the hull.</td>
<td>Reference: Ghoneim and Keinonen (1983)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MT Kashira, Baltic Sea, Arctic, 1984-90</td>
<td>Special type of pressure gauge installed inside the hull.</td>
<td>Reference: Kujala (1984)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB Sampo, Baltic Sea, 1989</td>
<td>External PVDF-pressure panel</td>
<td>Reference: Riska et al. (1990)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCGS Terry Fox, Arctic, 2001</td>
<td>External impact panel based on optic measurements</td>
<td>Reference: Gagnon (2008)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When it comes to uncertainty in the measurements, measurements based on the difference in the shear strain are less sensitive to the variation in the location of the load along the transverse frame than measurements based on the compressive strain normal to the hull. As mentioned above, the compressive strain normal to the hull decreases when the loading is having an effect further away from the sensor. Thus, the strain normal to the shell structure is a function of the amplitude, location with respect to the sensor, and the extent in the horizontal and vertical directions. When it comes to the shear strain difference, the determined loading is not sensitive to the height and location of the loading on the frame, as long as the loading is having an effect between the gauges. Outside the contact location, the shear strain over the web of the frame, the z-direction in Figure 5, remains relatively constant in the x-direction of the frame; see the distributions of the shear strains over the web in Figure 5. However, the shear strain-based measurements are sensitive to the location and length of the loading in the horizontal direction, the y-direction in Figure 5. As the measurements based on the shear strain difference are the least sensitive to the load height and locations and, thus, reliable in giving the load acting between the sensors, this work focuses on the measurements based on shear strain difference.
1.2.2 Challenges and uncertainty in shear strain measurements

When the measurements based on the shear strain difference are applied, the structure is known. The determination of the force-strain relation requires an assumption about the load location, shape, and pressure distribution (see e.g. Riska et al., 1983; Ralph et al., 2003). These are commonly kept constant through the measurements. However, in reality the load length, height, location, and pressure distribution in the contact vary, as illustrated by the full-scale measurements on board IB Sisu (Kujala et al., 1994); see Figure 4. Thus, the assumptions about the loading condition are not always correct, which creates uncertainty and variation in the measured loading, although the amplitude would be the same. More advanced inverse methods, where the area is not as limited, can be applied (see e.g. Liu et al., 2016). However, the inverse methods have their own uncertainties and problems related to the method. For these reasons uncertainty in the measurements should be studied.

As shown in Figure 4, the horizontal location of the loading varies when the ship moves in relation to the ice floes and can affect the shear strain measurements on the frame through torsion. However, as will be shown in this work, the torsional effect can also be diminished with proper planning of the instrumentation. The vertical location of the contact is affected by the draught and movements of the ship. As can be noted from Figure 5, the shear strain over

---

1. In Figure 5, the frame is loaded from the centre with a 10-kN point load. Fixed boundary conditions are applied to the plating at the ends of the frame. The height of the frame is 0.2 m, the length is 1.4 m, the width of the plating is 0.4 m, and the thickness of the plating and the frame is 20 mm.
the web at the location of the loading is different in comparison to other locations. If the loading has an effect at the location of the sensor, a contact problem occurs that hinders the shear strain measurements. In addition, if the location of the loading is not between the sensors, the measurements fail as the method does not account for the loading having an effect outside the measurement area. When merchant vessels are operating in ice conditions, the draught is adjusted in such a manner that the ice-induced loads affect the ice belt region, i.e. the structural area reinforced to sustain ice-induced loads. Furthermore, the level ice thickness is limited in first-year ice conditions and, thus, the loading is narrow. Thus, when the full-scale ice-induced measurements are conducted in first-year ice conditions, the instrumentation can be planned in such a way that the measurement results are not affected by the load height and the location in the vertical direction.

Simultaneously with the variation in the contact location, the dimensions of the loading vary significantly from short to long in the horizontal direction; see St. John and Minnick (1995) and Hänninnen et al. (2001). As the loads are measured from a local structure, the measurements only account for the location of the instrumentation and no knowledge about the surrounding structure is obtained. As the loading is transferred between frames, the loading having an effect outside the measurement area can affect the measurements. Although ice induces a line-like pressure pattern in first-year ice conditions, in multi-year ice conditions the pressure area can increase significantly in the vertical and horizontal directions and the pattern is not line-like and spreads over several transverse frame spacings; see e.g. Jordaan (2001). If the contact height increases to the thickness of the ice, the loading can have an effect at the location of the sensor that creates a contact problem.

As shown e.g. by Sodhi et al. (1998), the pressure distribution in the contact area varies significantly in the horizontal and vertical directions. However, as the situation varies temporarily, there is no clear description of how the pressure pattern should be accounted for. Thus, it is commonly taken as uniform. Although the shear strain difference-based measurements are not sensitive to the variation in the vertical direction (for transverse frames), the variation in the pressure distribution in the horizontal direction affects the load distribution between the frames and therefore the measurement response (Varsta, 1983; Körgeesaar et al., 2018).

Furthermore, the stiffness of the structure might cause difficulties for the measurements. The frames of the higher Polar Class ships are designed to sustain great loads. Thus, the response to smaller loads is minimal and difficult to measure, as the strain gauges are commonly optimized for higher loads. Thus, it can be impossible to separate the smaller loads from the noise of the carrier voltage of a measurement system. Conversely, lower ice class vessels are not suitable for ramming tests, as the structure might not be able to sustain the higher loads.

As the structure of the ship cannot be altered, the pressure distribution within the contact area in the horizontal direction and the load length are the main uncertainties affecting the measurement results in shear strain difference-based measurements for transverse frames. Thus, this work concentrates on the uncertainty related to the load length.

1.3 Objectives of the work

The aim of this dissertation is to study the uncertainty and the amount of variation in the ice-induced load related to load length when the shear strain measurement method is applied for transverse frames. Thus, the objectives of the dissertation are:
Objective 1: determine the ability of the structure and related structural parameters to transfer loading from the loaded frame to the surrounding structure;

Objective 2: determine the effect of the extension of the instrumentation on the variation in the determined loading;

Objective 3: determine the load length variation and corresponding statistical probability distribution of the load amplitude on a frame through full-scale measurements.

Figure 1 illustrates the different sources of variation in the measurements. Because of the variation in the mechanical processes, as depicted by Daley (1992), the length, height, location, spatial distribution, and amplitude of the ice-induced load on the hull vary. The load amplitude on the hull can be determined from the measured shear strains when the length, height, location, and spatial distribution are assumed. However, as the assumptions are not correct in all situations, the measurement technique brings additional uncertainty to the measurements and creates variation in the measured loading.

Figure 6 describes the research ensemble of this dissertation. The influence of structural parameters on the ice-induced load transfer (Objective 1) is studied in Papers [I] and [II]. Here, an analytical grillage model is defined to model the structural behavior and to parametrizes the load transfer. When the parameters affecting the load transfer are known, the knowledge is applied to estimate the uncertainty related to the extension of the instrumentation (Objective 2) in Paper [III]. The uncertainty analysis in Paper [III] is conducted with the full-scale measurements presented in Paper [IV]. When the effect of the extension of instrumentation on the statistical parameters of ice-induced loads is identified, the variation in the statistical parameters is studied and the effect of parameters to the probability distributions is described (Objective 3) in Paper [V]. In this paper plan, Papers [III] and [V] benefit the cumulative knowledge of research build on top of Paper [I], which presents also the effect of the load length on the magnitude of the loading on a frame. In addition, the effect of the load length on the probability distribution of load magnitudes on a frame is presented in Paper [I].

**Figure 6.** The research ensemble of this dissertation and the connection between the papers.
1.4 Limitations

Figure 1 and Figure 6 illustrate the different sources of variation in the ice-induced load measurements on a transversal frame. The ice conditions, ice failure mechanism, and ship operations cause variation in the magnitude of the loading, depending on the strength of the ice and how the ship is manoeuvred. The variation in the load amplitude resulting from these is considered to be due to natural variation in the condition and properties of the ice and influenced by human interaction and logistical requirements. Thus, the links between these parameters and the variation in the ice-induced load are left for other studies.

Uniform pressure distribution within the ice load patch is assumed here. Furthermore, it is assumed that the ice load has an effect between the sensors on the frame. These assumptions are justified as we are interested in the total ice-induced load on a frame and ships are operated in such a way that ice-induced loads appear on the ice belt.

Furthermore, the load length is determined in the aft shoulder area, where the frames are perpendicular in relation to the ice. It should be noted that curvature or slope in the structure would alter the results. However, it is not possible to study these with the instrumented structure applied in this thesis and they are therefore not included in the study.

This thesis concentrates on transversely framed structures, as this is common practice in ice-strengthened ships. Thus, the results are not directly applicable to longitudinally framed ships. The theoretical calculations are based on linear elastic analyses. This is justified as the design loads in the Finnish-Swedish Ice Class Rules are determined for the elastic region.
2. Structural ability to transfer loading

2.1 Structural response

As described in Chapter 1, ice induces a load on the ship hull. The load acts as a shear force on the transverse frame. Because of the ability of the structure to transport loading, a part of the loading is carried by the loaded frame and a part is transported to the adjacent frames by the hull plating connecting the frames. Thus, if a short loading is acting on a frame, the frame carries less loading than is acting on it when the adjacent supporting frames carry part of the loading. If the external loading is long, a part of the loading is transferred from the frame under consideration to the adjacent frames and a part is transferred from the adjacent frames to the frame being observed. If the load is long enough and uniform, the frame in the middle of the loading carries approximately the amount of loading acting directly on it. Figure 7 illustrates a case where 70% of the loading is carried by the loaded frame and 30% is transferred to the adjacent frames. The amount of loading carried by the directly loaded frame depends on the topology of the frame structure [P1]. Furthermore, the location of the load has an effect on the frame deflection and the measured ice-induced load.

![Figure 7](image-url)

**Figure 7.** Internal load transfer between frames when the loaded frame carries 70% of the external loading, for a short loading case (A) and a long loading case (B) [PIII].

When the loading affects a frame directly, the shear force on the frame is a result of the deflection. However, the frame adjacent to the loaded frame undergoes deflection and rotation. As the shear strains are measured on the surface of the frame, the deflection and rotation both affect the measurements. The shear strain resulting from the deflection depends on the magnitude of the shear force the frame carries. The shear strain resulting from the rotation depends on the side of the frame the loading is acting on with respect to the strain gauges; see Figure 8. If the loading is acting on the adjacent frame at the same side of the frame as that which is instrumented, the shear strains resulting from the rotation cause an increase in the total shear strains (the shear strain from the combined deflection and rotation). If the loading is acting on
the opposite side of the frame with respect to the instrumentation on the frame, the shear strain caused by the rotation is in the opposite direction to the deflection and the total shear strain on the frame surface decreases; see the left- and right-hand surfaces in Figure 8.

Figure 8. The shear strain in a cross-section resulting from the frame deflection in the z-direction and the rotation around the x-axis and the resultant shear strain on both sides of the frame [PI].

### 2.2 Effect of structural parameters on load transfer

In order to study the structural parameters affecting the load transfer between the frames, an analytical model was developed [PI, PII]. The analytical model follows a grillage analogy; see e.g. Tan and Montague (1991). Assume an external loading, \( F_{\text{EXT}} \), acting directly on the frame, which is modelled as a beam. The loading induces a bending moment, \( M_y \), and a shear force, \( Q_y \), on the frame. The adjacent parallel frames are connected to this beam by a transverse beam, which models the plate between the frames. This system forms the grillage. The frames support the transverse beam with vertical loads, \( Q_y \), and torsion moments, \( T_z \); see Figure 8. The beams are considered long and slender and they behave according to the Euler-Bernoulli kinematics. With these assumptions, the shear force and torsion moment affecting a frame can be determined, starting from the bending moment equations; see [PI, Chapter 3] for the derivation.

Earlier studies have suggested that the force diminishes rapidly and is negligible after a spacing of two frames away from the loaded frame; see e.g. Ralph et al. (2003). Thus, the grillage
analogy was applied to a simply supported and clamped frame system consisting of five frames and plating in [PI-III]. The equations for the load carried by the loaded frame, \( Q_{\text{mid}} \), and the external force, \( F_{\text{EXT}} \), were derived; see Equations (1-4) in [PIII]. The load carried by the loaded frame is determined with the grillage analogy and with FEA for several structures and the results are compared in [PIIII]. As the grillage analogy solutions followed a clear trend, the results are presented as a curve; see Figure 4 in [PIII]. Figure 4 in [PIII] shows good correspondence between the results when the thickness of the hull plating equals or is less than 20 mm.

As Figure 4 in [PIII] shows, the amount of loading transferred to the adjacent frames increases as a function of the ratios between the stiffness of the plating and frame and the ratio between the frame length and spacing. The possible error in the measurements related to the extension of the instrumentation and the length of the external loading depends on the ability of the structure to transfer loading internally. If the frames were extremely stiff, all the loading would be carried by the loaded frame. Thus, no uncertainty related to the load length in the horizontal direction would exist as the loaded frame would carry all the loading directly affecting it. As an opposite, an increase in the stiffness of the plating and the length of the frames increases the uncertainty in the measurements related to the variation in the length of the loading.

With these results, it is possible to estimate the uncertainty in the measurements related to the load length when the instrumentation is narrow. Suominen et al. [PIII] estimated the possible error resulting from the load length and the extension of the instrumentation for MS Kemira, MT Uikku, and S.A. Agulhas II; see Figure 9. Figure 9 shows that the internal load transfer is significant for MS Kemira and MT Uikku. As the reality is something between the clamped and simply supported boundary conditions, the load transfer between the frames is something between the solutions. As an example, an average of the two boundary conditions could be used to estimate the uncertainty. Figure 9 and Equations (1-4) in [PIII] can be used to estimate the uncertainty and in decision making when full-scale instrumentation is being considered. It should be noted that the effective breadth of the plating was considered in the bending stiffness calculation of the frame. The results presented in [PI], [PIII] and in Figure 9 applies the design curve for a uniform line load as defined by Schade (1951, 1953). Considering the design curve for a point load would decrease the term \( DL^2/EI_{fs}^3 \) by 7% as a result of the decrease in the stiffness of the frame.
2.3 Shear strain measurements

The response of the adjacent frames can be accounted for in the full-scale measurements by introducing an influence coefficient matrix. The external load on the structure is determined from the measured shear strain difference with an influence coefficient matrix $a$ and its inverse, $c$, using the relations

\[ \{F\} = [a]\{\Delta \gamma\} \text{ and } \{c_j\} = \Delta \gamma_i (F_j) \]  

where $\Delta \gamma_i (i = 1...m) =$ the shear strain difference measured on the frame $i$, $m =$ the number of instrumented frames, and $F_j =$ the external force exerted on the frame $j$. The diagonal terms define the force-strain relation of the frame under loading and the off-diagonal terms determine the response of the adjacent frames. Thus, the diagonal terms are only affected by the force carried by the loaded frame, while the off-diagonal terms consider the shear force and torsion of the adjacent frames. This can be shown with an analytical description of the matrix ([PI-II]); see Chapter 2.2.
When the shear force and torsion moment affecting a frame are known, a closed-form solution for the shear strain on the frames can be solved [PI]. The difference in the shear strain between the ends of the frame, \( \Delta \gamma \), is determined by calculating the shear strain occurring at on the lower and upper parts of the frame with the closed-form solution and then calculating the difference. The coefficients of the inverse influence coefficient matrix are calculated with the unit load principle. Equation (2) presents an example of the determination of the coefficient where the coefficients are determined for the first column, i.e. the case where the first frame is loaded. The rest of the coefficients are determined with the same manner by changing the location of the unit load.

\[
\begin{bmatrix}
  c_{i,j} & c_{i,j+1} & \ldots & c_{i,n} \\
  c_{i+1,j} & c_{i+1,j+1} & \ldots & c_{i+1,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  c_{n,j} & c_{n,j+1} & \ldots & c_{n,n}
\end{bmatrix}
\begin{bmatrix}
  1 \\
  0 \\
  \vdots \\
  0
\end{bmatrix}
= \begin{bmatrix}
  \Delta \gamma (F_{EXT,j})T_j(F_{EXT,j}) \\
  \Delta \gamma (F_{EXT,j})T_{i+1}(F_{EXT,j}) \\
  \ldots \\
  \Delta \gamma (F_{EXT,j})T_n(F_{EXT,j})
\end{bmatrix}
\]

The influence coefficient matrix \( a \) is the inverse of the matrix \( c \). It is common practice to determine the influence coefficients with Finite Element Analysis, FEA, as it is considered more accurate. However, analytical solutions enable the parameterization of the solution.
3. The extension of the instrumentation

3.1 The background of load amplitude as a function of load length

Because of the complexity and difficulty of measuring and describing the actual pressure distribution, the ice load is often taken as an average pressure over a certain area, i.e. a load patch, in the design of ship structures. The definition of an area can be divided into a global and local area (Jordaan et al., 2005). The global area denotes the projection of the structure onto the original shape of the intact ice field, while the local area considers sub-regions within the global area. Measurements on ships and offshore structures have shown that the ice-induced pressure decreases as a function of the area for both global and local pressures; see e.g. Sanderson, 1988; Frederking, 1999; Masterson et al., 2007; Taylor et al., 2010. However, the local pressure within the global pressure can increase as a result of an increase in the extent of the global contact area and exposure time when the average global contact pressure decreases (Jordaan et al., 2005; Ralph and Jordaan, 2013).

As the ice-induced pressure is line-like in the Baltic Sea ice conditions (Joensuu and Riska, 1989; Riska et al., 1990), the load length can be applied instead of an area. Thus, the loading is taken as a line load in the first-year conditions. This is accounted in the Finnish-Swedish Ice Class Rules (FSICR, 2010), where the line load as a function of the load length is embedded in a coefficient, $c_a$. The coefficient has been defined on the basis of full-scale measurements and damage surveys in the Arctic and Baltic Sea (Kujala and Vuorio, 1986; Kujala, 1991; Frederking and Kubat, 2007); see Riska and Kämäräinen (2012). The coefficient denotes the probability that the full length of the area under consideration will be under loading. In addition, the line load as a function of the load length was studied by Hänninen et al. (2001) and Suominen and Kujala (2015). Similarly to the pressure-area relation, the studies have shown that the line load decreases as a function of the load length; see Figure 3 in Suominen and Kujala (2015). These studies mainly focused on the spatial line load over the load length. As described by Frederking (1999), considering a time instance, the pressures on the panels can be grouped by adding the pressure on the adjacent panels together. This will give an average pressure for the different size of areas; note the similarity to the local pressure-area relation (Jordaan et al., 2005).

However, the actual load length, i.e. the number of adjacent frames simultaneously under the influence of the external loading, has not been studied to the same extent. Earlier studies have shown that short ice loads are more common, but the loading can extend over several frames (St. John and Minnick, 1995; Hänninen et al., 2001; Izumiyama, 2007). In addition to the load length, the concentration of the loading in the horizontal direction and loading on a frame as a function of load length have received little attention. Izumiyama (2007) studied the concentration of the loading in the horizontal direction with measurements on board USCGC Polar Sea by comparing simultaneous force recordings on the adjacent frames. The results
showed that the highest load recordings act on a few frames. Hänninen et al. (2001) also studied the total load on the whole instrumented area. The total force affecting the instrumented area showed no clear trend as a function of load length. Hänninen et al. (2001) assumed the results were affected by the low number of long loads in comparison with short loads, i.e. the exposure was higher for short loads. Numerical simulations have suggested that the probability distribution for the loading on a frame would be different for loading cases that are longer and shorter than the frame spacing; see Su et al. (2011a, b). However, this has not so far been validated with full-scale measurements.

3.2 The uncertainty in the measurements related to the load length

Because of the thick hull plating, the plates transfer the loads between frames, but also to the supporting web-frames. If adjacent frames are instrumented, an influence coefficient matrix can be applied in order to account for the effect of the adjacent frames on the measurements (see e.g. Riska et al., 1983; Minnick et al., 1990; Ralph et al., 2003 [PI]). The extent of the instrumentation over a specific area has varied from a single frame – see e.g. Kujala, 1989 – to several adjacent frames (see e.g. St. John et al., 1994; Ritch et al., 2008; [PIV]). Although the internal load transfer between the frames has been studied, the results have not been applied in the estimation of the accuracy of the full-scale measurements. On many occasions, the uncertainty studies have not been reported or discussed. In some occasions, the effect of the calibration load length has been estimated – see e.g. Kujala (1989) – and the effect of accounting for the adjacent frames when the loading on a frame is observed (Kujala and Vuorio, 1986; Minnick et al., 1990). However, these studies provided rough estimates of the uncertainty, but the uncertainty analysis was not reflected in the full-scale measurements.

When a frame is instrumented, the possible error in load determination, resulting from the false assumption about the external loading, depends on the ability of the structure to distribute the load to the adjacent frames. Naturally, the length of the external loading has an effect as well. The same applies for the outermost instrumented frames when several frames are instrumented. Earlier studies have shown that the extent of the load in the horizontal direction can vary from one to several frame spacings (Hänninen et al., 2001). Furthermore, Suominen et al. [PI] and Newmark (1938) showed that the ability of the structure to transfer loading depends on the ratio between the stiffness of the frame and of the plating and the ratio between the frame length and frame spacing. Thus, the difference in the results when only one frame is instrumented in comparison to several frames when the length of the external load varies from a spacing of one frame to a spacing of several frames is studied here. The data processing and load length definitions are described in Chapter 3.3.

3.3 Description of the applied full-scale measurement applied

3.3.1 The instrumentation of S.A. Agulhas II and data processing

This chapter employs the full-scale measurements on board the Polar Supply and Research Vessel S.A. Agulhas II in the Baltic Sea in March 2012 [PIV]. PSRV S.A. Agulhas II was built by STX Finland at the Rauma Shipyard (Rauma Marine Constructions at the time of writing) and was delivered in April 2012. The main dimensions of the ship are presented in Table 3. The ship is in the Polar ice class PC 5 and has a hull strength in accordance with DNV ICE-10.
Table 3. The main dimensions of S.A. Agulhas II [PIV].

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, bpp.</td>
<td>121.8  m</td>
</tr>
<tr>
<td>Breadth, moulded</td>
<td>21.7   m</td>
</tr>
<tr>
<td>Draught, design</td>
<td>7.65   m</td>
</tr>
<tr>
<td>Deadweight at design displacement</td>
<td>5000   t</td>
</tr>
<tr>
<td>Speed, service</td>
<td>14.0   kn</td>
</tr>
</tbody>
</table>

The hull of S.A. Agulhas II was instrumented with strain sensors at the bow, bow shoulder, and aft shoulder when she was under construction [PIV]; see Figure 10. As the instrumentation is most extensive at the aft shoulder, this study will focus on that area. The frame system in the instrumented area at the aft shoulder consisted of five transverse frames limited by web frames in the horizontal direction and decks in the vertical direction; see Figure 1 in [PIV]. The upper and lower parts of four frames in this area were instrumented with shear strain gauges following the principles presented in Chapter 2. The gauges were mounted on the bow side of the frames #41, #40, and #39½ and the aft side of the frame #40½. The gauge locations were 0.3 metres from the end of the frame, dlow and d_up, and 0.08-0.07 metres from the hull plating, d_sensor; see Table 4 and Figure 12. The plate thickness changes 0.4 metres above the lower end of the frame. Table 5 presents the structural parameters of the aft shoulder of S.A. Agulhas II.

Table 4. The location of the shear strain gauges.

<table>
<thead>
<tr>
<th>Sensor name</th>
<th>Frame</th>
<th>The side of the frame</th>
<th>The location on the frame</th>
<th>The distance from the hull plating, d_sensor [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#41</td>
<td>Bow &amp; Stern</td>
<td>Up Low Up Low Up Low Up Low</td>
<td>0.080 0.075 0.076 0.083 0.075 0.080 0.080 0.070</td>
</tr>
<tr>
<td></td>
<td>#40</td>
<td>Bow</td>
<td>Bow</td>
<td>0.080 0.075 0.076 0.083 0.075 0.080 0.080 0.070</td>
</tr>
<tr>
<td></td>
<td>#39½</td>
<td>Bow</td>
<td>Bow</td>
<td>0.080 0.075 0.076 0.083 0.075 0.080 0.080 0.070</td>
</tr>
</tbody>
</table>

Table 5. Structural parameters at the aft shoulder of S.A. Agulhas II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame length</td>
<td>1.4    m</td>
</tr>
<tr>
<td>Frame spacing</td>
<td>0.4    m</td>
</tr>
<tr>
<td>Web height</td>
<td>0.2    m</td>
</tr>
<tr>
<td>Web thickness</td>
<td>0.019  m</td>
</tr>
<tr>
<td>Plating thickness (lower part)</td>
<td>0.021  m</td>
</tr>
<tr>
<td>Plating thickness (upper part)</td>
<td>0.02   m</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>209    GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3    -</td>
</tr>
</tbody>
</table>
Figure 10. Instrumentation of the ship hull for ice-induced load measurements [PIII].

The strain-force relation was determined with FEA by applying a 10-MPa pressure load to an area of 0.01m*0.01m. The FE model was built using linear plate elements in the Femap software and the numerical calculations were conducted with NX Nastran (version 10.3.1). The finer mesh size in the region of interest was 0.005m*0.005m. The surrounding structure had a coarser mesh, with a mesh size 0.05m*0.05m. The density of the mesh at the location of the sensor should be fine enough to model the change in the shear strain accurately. Figure 11 shows the shear strains over the web when the loading is affecting frame #41. As can be noted, the mesh is dense enough to model the shear strain changes accurately over the web. Additionally, the difference in the shear strain on the different sides of the frame is notable on the adjacent frame. Rigid boundary conditions were applied to all the edges where the actual structure continued by constraining all degrees of freedom. See [PI, PII] for further details about the structure, the instrumentation, and the FE model. The model was validated with the calibration pull [PI, II] and by comparing it to the solutions from the grillage analogy [PI].

The influence coefficient matrix for the aft shoulder was defined as described in Chapter 2; see Equation (3). The shear strain gauges consisted of two sensitive measuring areas, see Figure 12. The distance between the centres of the sensitive areas is 0.036 m. Each sensitive area covered four elements in the FE model, see Figure 12. The shear strains at the locations of the sensors were determined by taking an average from the eight elements covering the sensitive areas of a gauge. In order to study the effect of the load length on the measured loading in the case of single frame instrumentation, the strain-force relation coefficients for the individual
frames at the aft shoulder were determined by observing the relation one frame at a time; see Table 6.

**Figure 11.** The elemental shear strains over the web of a frame at the location of a sensor when the frame #41 is loaded. Each mark denotes an element. Plus marks denotes the bow side of the frame surface and cross the stern side of the frame surface.
Figure 12. A frame from the FE model and a schematic picture from the shear strain gauge. The blue areas in the frame denotes the elements from which the shear strain was determined, i.e. the sensitive areas of the sensor.

\[
a = \begin{bmatrix}
320.39 & 16.20 & -2.81 & 0.70 \\
13.19 & 329.10 & -58.67 & 4.79 \\
2.58 & -62.96 & 332.56 & 14.47 \\
-0.98 & 18.41 & -57.39 & 310.12
\end{bmatrix} \times 10^3 \text{kN/strain}
\] (3)

Table 6. The structural response coefficients when frames are considered separately.

<table>
<thead>
<tr>
<th>Frame</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>#41</td>
<td>320*10³ kN/strain</td>
</tr>
<tr>
<td>#40½</td>
<td>317*10⁴ kN/strain</td>
</tr>
<tr>
<td>#40</td>
<td>324*10² kN/strain</td>
</tr>
<tr>
<td>#39½</td>
<td>312*10³ kN/strain</td>
</tr>
</tbody>
</table>

3.3.2 The measurement voyage and data processing of the measurements

The measurements were conducted in the northern part of the Baltic Sea on March 21-22, 2012. The mean thickness of the solid ice was approximately 0.3 metres (Suominen et al., 2014). The mechanical properties of the ice measurements showed that the ice was typical spring season ice [PIV]. See [PIV] and Suominen et al. (2014) for more detailed descriptions of the general and measured ice conditions during the measurements. Altogether, 24 hours’ worth of data was collected. The whole data set is applied in this study.

The shear strains on the frames were recorded continuously with a frequency of 200 Hz. After the strains are converted into ice-induced forces with the influence coefficient matrix, the load events are identified from the time history with Rayleigh separation. The separation is based
on comparing the minimum and maximum values. If the minimum between two maxima is smaller than the lower maximum multiplied by the separator value, the maxima are considered to be separate cases; see [PV] for a more detailed description. As the systems in full-scale measurements are scaled to measure loads of over 1000 kN, the threshold is commonly applied to eliminate the noise in the measurements. The threshold neglects values below it.

**Figure 13.** A short and a long loading travelling over the instrumented area. A) A 3D presentation of the load time history. B) and C) Time histories from each frame separately. The blue circles indicate the maximum load on each frame during the long load event. The orange line indicates the number of frames under loading, i.e. the estimated load length.

After the loading events are identified from the time history of a single frame, the loading length is taken as the number of adjacent frames exceeding the threshold at the same instant in time. Figure 13C illustrates the time history of the load length determined with this methodology. Naturally, the extent of the instrumentation imposes limitations on the measurements. If the loading extends to the frames that are at the boundaries of the instrumented area, it is possible that the loading continues to an area that is not instrumented [PI]. Figure 13 presents an example of loading events that were one and four frame spacings long. In the case
presented in Figure 13, all the frames experience their highest maxima when the load length is four frame spacings long.

3.4 Load length distribution and variation in the determined loading resulting from the extension of the instrumentation

As the outermost frames, #41 and #39½, contain higher uncertainty in the load length determination because there are un-instrumented adjacent frames, the load events were identified for the two middle frames, #40½ and #40, separately. The measured shear strains were first converted into ice-induced loads with the influence coefficient matrix. Then the load events were identified with the Rayleigh separation. The sensitivity of the number of loads, the mean value of loads and the standard deviation of loads was tested for the threshold and Rayleigh separator values, see Table 7. Table 7 shows that the statistical parameters and number of loads are not sensitive to the separator values. However, the threshold has a significant impact to the statistical parameters and the number of loads, see Table 7 and Paper [1]. In order to be consistent with earlier studies, the separator was chosen to be 1/2, see e.g. Kujala (1989). Observations of open water sections showed that the noise in the signal was under 10 kN. Thus, 10 kN was chosen as the threshold. Figure 14 presents the number of ice load amplitudes for different load lengths. Figure 14 shows that short loads are more common than longer loads, but are smaller in magnitude.

Table 7. The number of loads, mean value of loads and standard deviation of loads on frame #40½ and #40 for different thresholds and Rayleigh separator values.

<table>
<thead>
<tr>
<th>Separator value</th>
<th>Frame</th>
<th>1/2</th>
<th>1/3</th>
<th>1/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td></td>
<td>#40½</td>
<td>#40</td>
<td>#40½</td>
</tr>
<tr>
<td>10 kN</td>
<td>Number of loads</td>
<td>7432</td>
<td>3447</td>
<td>7268</td>
</tr>
<tr>
<td></td>
<td>Mean value [kN]</td>
<td>15.6</td>
<td>25.9</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td>Standard deviation [kN]</td>
<td>6.27</td>
<td>15.5</td>
<td>6.31</td>
</tr>
<tr>
<td></td>
<td>Number of loads</td>
<td>1259</td>
<td>1883</td>
<td>1250</td>
</tr>
<tr>
<td></td>
<td>Mean value [kN]</td>
<td>26.6</td>
<td>35.3</td>
<td>26.6</td>
</tr>
<tr>
<td></td>
<td>Standard deviation [kN]</td>
<td>7.34</td>
<td>15.2</td>
<td>7.36</td>
</tr>
<tr>
<td></td>
<td>Number of loads</td>
<td>260</td>
<td>1004</td>
<td>259</td>
</tr>
<tr>
<td></td>
<td>Mean value [kN]</td>
<td>37.7</td>
<td>44.9</td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td>Standard deviation [kN]</td>
<td>8.76</td>
<td>15.3</td>
<td>8.78</td>
</tr>
</tbody>
</table>
Figure 14. The number of load events on the frames #40½ and #40 for different load lengths during the Baltic Sea ice trial. The events are organized into histograms with a 10-kN bin size on the basis of the loading on the frame determined with the matrix solution. Note the logarithmic scale on the y-axis of the upper plots. [PIII]

Figure 15 presents the measured maximum load on a single frame as a function of the load length during the Baltic Sea ice trial. Figure 15 confirms that the load magnitude is smaller for the short loads. This indicates that the loading on the hull has to be long enough for the highest maximum on a single frame to occur. On the contrary, Izumiyama (2007) suggested that the higher loads act on shorter load lengths. However, the load length was defined differently and the data contained only a few long loading cases. The studies of the local pressure have suggested that an increasing global pressure area increases the exposure of the local pressure by increasing the time the load acts on the structure, which increases the probability of greater local pressures occurring (Jordaan et al., 2005; Ralph and Jordaan, 2013). In order to clarify this, the duration of each load event was determined for both frames, see Figure 16. The start of a load event was determined to be the time when the load signal rise above the threshold. The end of the event is the time when the signal decreased below the threshold. If a second load event occurred before the signal decreased under the threshold, the minimum load level between the two load maxima was considered to be the end of the first load event and the beginning of the following event. Figure 16 indicates an increasing load level as a function of the loading time. The low load level in the events with long duration is considered to be a result of few load events - note the logarithmic scale in the number of the load event durations.
Figure 15. The load on the frames #40 and #40½ as a function of the actual load length, modified from [PI].

Figure 16. The duration of determined loading events (the red plus marks) and the compiled histogram of the loading events with 0.05 second bin range (the black lines). The left-hand side vertical axis denotes the load level in the separate load events (the plus marks) and the logarithmic right-hand side vertical axis the number of events in the histogram.

In order to study the effect of the extension of the instrumentation to the determined load amplitude, the measured shear strains from the loading events were gathered from the events presented in Figure 10. After the strains from the loading events became available, the loadings on the frames #40½ and #40 were calculated from the strains when the frames were considered separately – see Table 6 – and jointly with the influence coefficient matrix; see Equation (3). When the frames were considered separately, the strains were taken from a single frame at a time. When the frames were considered jointly, the strains on all the frames were observed and the loading on the frames #40½ and #40 was determined with Equation (3).

The effect of the extension of the instrumentation was defined by calculating the difference in the loadings defined with the influence coefficient matrix and frames separately; see Figure
Positive values indicate that the magnitude is higher when the frames are considered separately. As can be noted, the difference is not significant for loading events that are one frame spacing long, but increases for the longer and higher-amplitude loading cases. The differences in the results were organized into ranges based on the histograms presented in Figure 14 and the mean value and standard deviation of the differences were calculated; see Figure 17. The ranges with fewer than three samples were disregarded in the calculations. The average difference for loads one frame spacing long and for small loads with a longer loading is close to zero and the scatter is insignificant. However, the mean difference and standard deviation increase as a function of the load magnitude; see Figure 17. The mean difference for load events longer than two frame spacings is around 10%. This is close to the difference estimated with the grillage analogy; see Figure 9.

Figure 17. The mean difference, $\mu$, of the loads classified into 10-kN bins on the basis of the measured load with the matrix. $\sigma$ denotes the standard deviation of the difference in the load bin. [P111]
4. The load length distribution and the load amplitude probability distribution on the frame

4.1 Variation in short-term ice-induced load amplitudes on a ship hull and related probability distributions

Because of the randomness of the ice-induced loads on the ship hull, the loads have been studied with probabilistic methods. Likhomanov (Kheisin and Popov, 1973) was the first to notice that the number of loads on a region of the ship hull in a unit of time follows Poisson’s law and the probability distribution of the load amplitudes follows Pearson type III probability distribution. Later probabilistic studies applied exponential probability distribution (Jordaan et al., 1987; Jordaan et al., 1993; Taylor et al., 2010) and Gumbel I probability distribution (Kujala, 1994) to describe the probability of the maximum ice-induced loads on the ship hull. The statistical studies of the measured short-term ice-induced loads have shown that the Weibull probability distribution (Kujala et al., 2009; Suominen and Kujala, 2010; Suyuthi et al., 2012a, 2012b; Kotilainen et al., 2017 [PI]) gives the best fit to the measured data. In addition, studies have shown that the exponential or logarithmic normal probability distribution could be used to describe the measured short-term ice-induced loads (Kujala and Vuorio, 1985, 1986; Suominen, 2011; Suyuthi et al., 2012b [PI]).

As the parameters of the probability distributions can be estimated on the basis of these statistical parameters of the measured loads, the statistical parameters of the measured loads are of importance. In addition, the standard deviation should be reflected in the mean value in order to understand the significance of the variation. The ratio between the standard deviation and the mean value is expressed with the coefficient of variation, or its inverse:

\[ CoV^{-1} = \frac{\mu}{\sigma} \quad (4) \]

where \( \mu \) is the mean value and \( \sigma \) is the standard deviation of the sample. Earlier studies indicate that an interesting connection between the standard deviation and the mean value of the measured ice-induced loads exists as the mean value increases in linear-like fashion as a function of the standard deviation (Kujala et al., 2009; Suominen and Kujala, 2010; Suominen, 2011); see Figure 18. In Figure 18, the labels “Level ice” and “Ridged ice” refer to independent operation in ice conditions with no significant deformation and independent operation in ice conditions containing ridged or rafted ice, respectively.
The study on the connection between the standard deviation and the mean value was continued in [PV] with the measurements on board MT Uikku and MS Kemira in the Baltic Sea; see Table 2 in [PV]. The bow, midship, and stern of MT Uikku were originally instrumented for ice-induced load measurements in an Arctic expedition in 1998 (Kotisalo and Kujala, 1999a, 1999b). The instrumentation was repaired in 2000 and three research voyages were conducted in the Baltic Sea in 2003 (Lensu, 2002a; Lensu and Karttunen, 2001; Karttunen, 2001; Hänninen, 2003). A detailed description of the instrumentation is given by Kotisalo and Kujala (1999a) and Lensu (2002a). The loads were recorded continuously with 200 Hz during these voyages and the load events were identified using a Rayleigh separator value of $\frac{1}{4}$ and a 10-kN/m threshold. Ten-minute load histograms were produced.

Three frames of MS Kemira at the bow shoulder, midship, and stern shoulder were instrumented for long-term measurements in the Baltic Sea in 1984 (Kujala, 1989). However, the system was adjusted to measure short-term ice-induced loads for nine manned research voyages during the winters of 1987 and 1988. The Rayleigh separator was $\frac{1}{2}$. The threshold was set by the system as the lower limit of the smallest load class; 25 kN/m for the bow and 18 kN/m for the midship and stern frames (Suominen and Kujala, 2010). The ice-induced load data was recorded as one-hour ice-induced load histograms (Suominen and Kujala, 2010). A detailed description of the instrumentation is given by Kujala (1989).

All the measurements showed the same phenomenon; the measured standard deviation increases in a close-to-linear fashion as a function of the mean value, and the inverse coefficient of variation, $\text{CoV}^{-1}$, decreases with an exponential trend as a function of the measured maximum ice-induced load; see Chapter 3 in [PV]. The statistical parameters of the full-scale measurements can be explained with the numerical formulation of the statistical parameters by assuming that 1) the smallest ice-induced loads constitute the initial datasets and, 2) the measured maximum ice-induced load is considered as the value added to the initial dataset; see Section 2.2 in [PV]. This is justified, as the ice-induced loads concentrate on the smallest load classes in all the periods. Thus, the smallest load classes form the initial dataset, which is the same for all the measurement periods with the same threshold value. Furthermore, the maximum value is always greater than or equal to the mean value. Therefore, the measured maximum can be taken as the added value ($x_{n+1}$).
4.2 Variation in the statistical parameters resulting from the extension of the instrumentation

As a follow-up to the study on the effect of the extension of the instrumentation on the determined load amplitudes as a function of load length – see Chapter 3.4 – the effect on the statistical parameters is studied. The strains were recorded in five-minute continuous time histories with 200 Hz. The ice-induced load time histories were determined, with the frames being considered both separately and with the influence coefficient matrix, as described in Chapter 3.4. After the conversion, the ice-induced load events were identified from the time history with Rayleigh separation. The factor and threshold applied in the Rayleigh separation were ½ and 10 kN, respectively. The mean values, standard deviation, and coefficient of variation of the load events were calculated for each period. As the calculation of the statistical parameters is more relevant for cases with a number of samples, the parameters were calculated only for the periods for which more than 50 load events were identified with both methods. The calculated statistical parameters are presented in Figure 19 and the difference in Figure 20.

Figure 19 shows the same trend as that observed by Suominen and Kujala [PV]. The differences are minor for smaller values of statistical parameters, but increase for higher values, being up to 10% higher for separate frames. Generally, when the loads are defined separately for single frames, the mean values and standard deviations are higher; see Figure 19 and Figure 20. The difference in the coefficient of variation is not as significant, as both the mean value and standard deviation are higher when separate frames are considered. However, on average, the coefficient of variation increases slightly for separate frames; see Figure 20. As noted above, the difference between the matrix and separate frames is insignificant for short loads and increases for longer load lengths. Suominen et al. [PI] showed that the highest loads on a single frame occur when the external loading is long. Thus, the greater difference in the higher values of the statistical parameters between the separate frames and matrix results is expected to be due to the maximum load occurring with longer load lengths. Furthermore, the difference is insignificant for smaller statistical parameter values, as the load lengths are generally short.
Figure 19. Standard deviation as a function of mean value, on the left, and the coefficient of variation as a function of standard deviation, on the right, from the same five-minute period. The circles and plus signs denote the statistical values determined with the matrix and frames separately, respectively. The lines connecting the circles and plus signs indicate which solutions are from the same five-minute period.

Figure 20. The difference in the mean value, standard deviation, and coefficient of variation determined with the matrix and frames separately as a function of the values determined with the matrix. The values correspond to the length of the lines presented in Figure 19.

4.3 The effect of the load length on the amplitude probability distribution

This section utilizes the measurements from S.A. Agulhas II in the Baltic Sea presented in Chapter 3.3. The loading events were identified and classified on the basis of the load length as described in Chapter 3.3.2. The Rayleigh separator value utilized was ½ and three threshold values were applied – 10, 20, and 30 kN; see Figure 13 in [PI]. After the loading events had been categorized on the basis of the load length and threshold for the frames #40 and #40½,
the probability distributions were fitted to the load amplitude distributions. Because of the threshold that was applied, the distributions are truncated. Thus, the 3-parameter Weibull, 3-parameter lognormal, and 2-parameter exponential probability distributions are utilized in the study.

\[
f_W(x; \beta_W, \eta_W, \gamma) = \frac{\beta_W}{\eta_W} \left( \frac{x - \gamma}{\eta_W} \right)^{\beta_W - 1} e^{-\left( \frac{x - \gamma}{\eta_W} \right)^{\beta_W}}
\]

\[
f_E(x; \lambda_E, \gamma) = \lambda E^{-\lambda(x-\gamma)}
\]

\[
f_{LN}(x; \mu_{LN}, \sigma_{LN}, \gamma) = \frac{1}{(x - \gamma)}\sigma_{LN}\sqrt{2\pi} e^{\frac{[\ln(x-\gamma) - \mu_{LN}]^2}{2\sigma_{LN}^2}}
\]  (5)

\(\gamma\) is the location parameter, which equals the threshold that was applied. The shape and scale parameters of the Weibull distribution, \(\beta_W\) and \(\eta_W\), the rate parameter of the exponential distribution, \(\lambda_E\), and the location and scale parameters of the lognormal distribution, \(\mu_{LN}\) and \(\sigma_{LN}\), were estimated for each category with the MATLAB 2015b built-in probability distribution fitting tool and validated with the Minitab 17 fitting tool for two cases. Figure 21 shows an example of the fit of the probability distributions to the ice loads measured on the frame \#40½ for different load lengths with a 20-kN threshold. The fit of the distributions to the measured data was estimated visually and tested with three goodness-of-fit tests, the Anderson-Darling, Kolmogorov-Smirnov, and Chi-Square tests [PI].
Figure 21. The measured load amplitude distributions on the frame #40½ with a 20-kN threshold for different load lengths and the fitted probability distribution functions of the Weibull, lognormal, and exponential distributions. Note the different ranges on the y- and x-axes [PI].

The goodness-of-fit test and visual observations show that the Weibull probability distribution models the measured loads the best; see Table 2 in [PI]. However, the lognormal and exponential probability distributions can be accepted in some cases. This is in accordance with earlier findings (Suyuthi et al., 2012b). In addition, the study showed that the shape of the load probability distribution is exponential-like for the short loading cases and lognormal-like for the longer loading cases. Simulations have indicated similar behaviour (Su et al., 2011b). The Weibull probability distribution is able to model the load amplitude distributions on a frame for short and long loadings as its shape is exponential-like when the shape parameter is smaller than one, $\beta_W<1$; it equals the exponential distribution when $\beta_W=1$ and its shape is lognormal-like when $\beta_W>1$. 

\[ \beta_W < 1 \text{: exponential-like} \]
\[ \beta_W = 1 \text{: exponential distribution} \]
\[ \beta_W > 1 \text{: lognormal-like} \]
5. Conclusions

5.1 Summary of main findings

The thesis aims to study the uncertainty in the ice-induced loads measured in full-scale and estimate the amount of the variation originating from the scatter of the actual load length. An analytical grillage model is derived to determine the shear force and torsion on the loaded and adjacent frames and the shear strain distribution on the surfaces of the frames [PI, PII]. The model was applied to explain how instrumentation on the different sides of the frames reduces the effect of torsion on the measured differences in the shear strains on the frame. Diminishing the torsional effects reduces the possible error related to the load location in the horizontal direction [PI]. This highlights the importance of reporting the location of the strain gauges accurately and offers the possibility of estimating the uncertainty related to the torsion on the frame. However, the reporting of the instrumentation in the earlier studies is lacking on many occasions; see the references listed in Table 1. Thus, it is not possible to estimate the uncertainty related to the horizontal location in the earlier measurements.

The structural parameters affecting the load transfer between frames are determined analytically and with FEM [PI, PII]. The study showed that the ratio between the stiffness of the frame and the hull plating affects the amount of loading carried by the loaded frame, as indicated earlier by Newmark (1938). In addition, it was shown that the ratio between the frame spacing and frame length affects the load transfer. On the basis of the load transfer study, a method to estimate the possible error in the measurements as a function of the length of the external loading was presented [PI-III]. The uncertainty and variation in the measurements are not affected by the extension of the instrumentation when the loading is short, but increase when the load length increases beyond the instrumented area [PI-III]. The method can be applied when the extent of the instrumentation for full-scale measurements is being determined.

Load length distribution based on full-scale measurements is presented for first-year ice in the Baltic Sea [PI, PIII]. The measurements from the aft shoulder of S.A. Agulhas II showed that short loading cases are more common than long cases, which is in line with earlier results (St. John and Minnick, 1995; Hänninen et al., 2001; Izumiyama, 2007). It was shown that the loading on a frame increases as a function of the external load length in the full-scale measurements [PI]. Furthermore, the load magnitude increases as a function of the length of the duration. These are in line with earlier studies, where the possible increase in the local pressure as a function of the global area has been explained by greater exposure (Ralph and Jordaan, 2013; Ehlers et al., 2015). On the contrary, Izumiyama (2007) showed that the highest loads are short. However, Izumiyama (2007) studied the load in the bow area and defined the load length differently from the ship speed and duration of the loading. This requires an assumption of constant load length, which is not valid in many cases. Furthermore, it cannot take into account the possibility that the loading starts to affect the adjacent frame and is transported to
the instrumented frame. Thus, the load lengths presented in this dissertation are considered more reliable.

The effect of the load length on the mean value, standard deviation, and probability distribution of the load amplitude on a frame is explained [PIII]. The effect of the extension of the instrumentation was studied with the instrumentation at the aft shoulder of S.A. Agulhas II. It was shown that the effect of the extension is insignificant when the external loading affects only one frame. However, the loading can be approximately 15% higher for single-frame instrumentation than multi-frame instrumentation when the length of the external loading increases. Furthermore, the measured five-minute mean value and standard deviation can be up to 10% higher for the single-frame instrumentation.

Kujala et al. (2009) were the first to observe a linear-like increase in the measured mean values of the ice-induced load on a frame as a function of the standard deviations. However, this study was the first to explain the phenomenon through statistical methods [PV]. Thus, the general trend is a mathematical phenomenon. However, the variation in the measured statistical parameters can result from the different ice conditions and operational profiles of the vessels between the measurement periods. The ice conditions and vessel operations may alter the initial standard deviation, mean value, and numbers of samples. Therefore, the measured statistical parameters can represent points from a set of curves that have variation in the initial parameters, which are specific for certain ice conditions and vessel operations. In addition, the variation can also be partly a result of the variation in the external load length and the extension of the instrumentation.

The statistical study showed that the Weibull probability distribution gives the best fit to the probability distribution of the measured load magnitude on a frame. This is in accordance with earlier studies (Kujala et al., 2009; Suyuthi et al., 2012b, Kotilainen et al., 2017). Furthermore, it was observed that the shape of the probability distribution of measured loads on a frame is exponential-like for short loads and lognormal-like for long loads. Numerical simulations have shown similar results (Su et al., 2010b), but the phenomenon has not been observed in earlier full-scale measurements. However, it should be noted that the shape of the gamma probability distribution is similar to that of the lognormal probability distribution and it can be shown that the sum of the exponential probability distributions follows the gamma probability distributions. Thus, as the ice-induced loads on separate frames follow exponential distribution, the sum of the distributions seen in the observed frame would follow gamma distribution. However, as shown by Ochi (1990), Weibull, gamma, lognormal, and exponential distributions are special solutions of the generalized gamma probability distribution. Thus, the generalized gamma distribution would give an equal fit to, or one better than, the above-mentioned probability distributions.

5.2 Recommendation for full-scale instrumentations

When full-scale measurements are planned, the key issue is the extension of the instrumentation. An extensive instrumentation increases the accuracy of the measurements and enables more thorough study. However, each channel increases the costs through manual work, e.g. mounting the sensors, and the required hardware, e.g. channels in the Data Acquisition (DAQ) systems. The method presented in this work can be employed to estimate the uncertainty related to the measurement and determine the minimum number of instrumented frames to obtain reliable measurements. Instrumenting both adjacent frames will give the most reliable
results for the middle frame. It is not reasonable to give an exact limit here on the point at which instrumenting a single frame would not be useful as the effect of the operational conditions and ice conditions on the ice-induced loads is not fully known. Although the method can be applied to estimate the uncertainty related to the load length, it should not be applied directly as a correction factor, as a reliable method to determine the load length with a single-frame instrumentation is lacking. Furthermore, when full-scale measurements are reported and published, more emphasis should be put on describing the actual structure, the sensor location, and the loading conditions employed in the determination of the force-strain relation, i.e. the influence coefficient matrix.

When measurements are planned, the sensitivity of the sensors should be chosen. This should be done by considering the instrumented structure and expected maximum loading. From the assumed loading and knowledge of the structure, it is possible to estimate the expected range of strains and the sensors can be chosen. When the sensor locations on the frame web are planned, it should be noted that the shear strain and stress obtain their maximum value at the neutral axis of the frame. Generally, FEM should be applied in the identification of the neutral axis as more complicated structures can be analyzed, e.g. if the sensor has to be placed in close proximity to the brackets. In the analysis, the neighbouring frames should be accounted for by modelling the frames or boundary conditions, as the surrounding structure will have a stiffening effect on the frame through the effective breadth of the hull plating. If FEM is not available, the effective breadth of the plating should be accounted for in the analytical determination of the neutral axis.

Furthermore, it is commonly known that the principal planes are orthogonal and perpendicular. The planes of stationary shear stresses are oriented at $45^\circ$ with respect to the principal planes, i.e. the maximum and minimum shear stresses occur at $\pm 45^\circ$ with respect to the principal stresses. Thus, when the shear strain measurements are applied, the two sensors should be oriented towards these directions with respect to the neutral axis. This increases the sensitivity of the measurements to loads, i.e. the measurements can be amplified. Furthermore, it can be derived from the basic definitions of the strain measurements that the shear strain can be measured by using only the two gauges with these orientations. If the neutral axis is located correctly, the third gauge in a strain gauge rosette is along the neutral axis and no strain should occur. In this case, the sum of the two gauges measuring the shear strain will give the strain in the $z$-direction of the frame, which should also be negligible, unless the force is acting directly at the location of the sensor.

As noted in Chapter 1.2.2, the shear strain measurements are not sensitive to the location of the loading in the vertical direction if the loading is clearly having an effect between the sensors. It is possible to execute this by placing the sensors as far apart from each other on the frame at the operational waterline as possible. However, the supporting structures, e.g. brackets, can increase the stiffness significantly. Thus, it can be beneficial to place the sensors between the brackets. As discussed earlier, if the draught changes significantly or in the event of multiyear ice, the load might occur at the location of the sensor. In this case, a contact problem occurs that increases the uncertainty significantly. The possibility for this can be estimated by recording the draught of the ship regularly. Another possibility is to use the shear strain measurements. As noted, the strain in the $x$ and $z$-directions along the neutral axis should be close to zero if the loading is not having an effect in the near vicinity. Thus, if the sum of the shear strain gauge (the sum of gauges pointing at $\pm 45^\circ$ directions with respect to the neutral axis) differs significantly from zero, a contact problem can be expected and the measurement results
should be questioned. As noted in Papers [I] and [II], the torsion related to the horizontal location of the contact affects the shear strain measurements. This effect can be reduced by placing the shear strain gauges on different sides of the frame, e.g. the gauge on the upper part of the frame on the bow side of the frame and the lower gauge on the stern side of the frame.

As highlighted by the study on the duration of ice load events, the sampling frequency should be high enough to measure the events. The duration of loading events of 100 kN and higher is equal to, or longer than, 0.1 seconds. If the interest is in smaller loads, for example if fatigue is concerned, the duration is of the order of 0.01 seconds. It should be noted that the measurement frequency should be higher than the duration of the event to catch the phenomenon.

5.3 Future work

The grillage model developed to estimate the possible error is not accurate when the thickness of the hull plating is greater than 0.02 m. As the thickness of the hull plating for higher Polar Class ships is over 0.02 m, the method should be developed further to cover a broader range of vessels. The model could be developed further by accounting for the coupled terms assumed to be zero in this work. Furthermore, more advanced plate theories (such as Reissner-Mindlin) and beam theories (e.g. Timoshenko beams) could improve the accuracy and increase the coverage of different structures. If the model is applied for cases where the loading is closer to the location of the sensor, the definition of the effective breath should be revisited (the design curve for uniform loading was applied here). Furthermore, the effective length of the frame was taken as the total length. In the case of a real structure, the frames commonly have brackets, which changes the effective length. Naturally FEA solves these problems, but fails to parametrize the main effects.

The study focused on the uncertainty and variation related to the load length in shear strain difference-based full-scale ice-induced load measurements. The effect of the load location in the vertical direction, height, and spatial distribution on the measured loading were not studied. However, these can have an impact on the measurements if the loading affects the vicinity of the gauges. Thus, the effect of these factors in the contact problem should be studied and possible methods to reduce the effect or estimate the uncertainty should be developed. Furthermore, the ice-induced load measurements based on the compressive strain perpendicular to the hull were not considered in this work. Thus, the uncertainty in these measurements related to the load length, height, location, and pressure distribution should be studied as well.

This thesis concentrated on transversely framed structures as this is a common design practice in ice-strengthened ships. Thus, the results are not directly applicable to longitudinally framed ships. Furthermore, the load length is determined in the aft shoulder area, where the frames are perpendicular with respect to the ice. It should be noted that curvature or slope of the structure would alter the results. However, it is not possible to study these with the instrumented structure applied in this thesis and they are therefore not considered in the study.

As the histogram of the short-term ice-induced loads decreases exponentially, the threshold applied in the measurement has a significant impact on the initial mean value, standard deviation, and number of ice-induced loads. Thus, the threshold used in the measurements should be taken into account when the short-term measurements are analyzed. However, the study of the lowest applicable threshold in the full-scale measurements requires an in-depth study of the measurement system and the definition of ice-induced loads from the measured time history, which should be studied in the future. This study applied Rayleigh separation to identify
and separate the ice-induced loads. Besides the Rayleigh method, other methods to define the ice-induced loads, such as the event maximum method (Jordaan et al., 1993) or up-crossing rate (Li et al., 2010), exist. However, the methods are not based on the physical processes of the ship-ice interaction (e.g. bending or crushing failure). In order to improve the load identification significantly, a method based on the physical processes or that has its background in these should be developed to identify different loading scenarios (compare to the optical pattern recognition) from the measurements.

The work briefly described the effect of the ice conditions and ship operations on the pressure distribution on the hull of the ship, the height and length of the loading, and the magnitude of the loading. In order to obtain a better overall understanding of the ice conditions and ship operational parameters of the ship affecting these loading attributes, more work on applying advanced statistical methods in the analysis of the data is needed (see e.g. Kotilainen et al., 2017). Furthermore, in order to improve the understanding of the mechanics between the ice floes and ships and mechanical processes in the structure-ice interaction, more laboratory experiments and simulations are needed (see e.g. Su et al., 2011a, b; Paavilainen et al., 2013; Daley, 1991; Kim and Quinton, 2016). Thus, these matters should be studied in the future to get a better understanding of the parameters and processes that have an effect.

Kujala (1994) developed a probabilistic method to predict the return period of extreme ice-induced loads with Gumbel I distribution. Gumbel I distribution was defined based on the statistical parameters of the ice-induced loads, which were connected to an equivalent ice thickness. However, the full-scale measurements showed that the inverse coefficient of variation of ice-induced loads is not constant, as was assumed by Kujala (1994). Connecting the inverse coefficient of variation to the ice conditions, in addition to the mean value, could improve the method proposed by Kujala (1994). However, more research on the effect of the ice and operational conditions on the coefficient of variation of ice-induced loads is needed in the future.

In order to obtain more reliable information on the loading acting on the ship hull and environmental conditions in full-scale, new measurement methods should be developed and applied. As an example, optics-based measurement methods have been applied (see e.g. Gagnon, 2008 for ice-induced load measurements; Kulovesi and Lehtiranta, 2014 for ice thickness measurements). The new methods can reduce the uncertainty and error in the measurements and should be developed constantly in the future.

The importance of the ultimate strength and load-carrying capacity of the structure was highlighted at the beginning of the work, but not discussed further. When the knowledge of the ice-induced loading – the dimensions and spatial pressure distribution – increases, the knowledge should be employed in the ultimate strength analysis (see e.g. Kõrgesaar et al., 2018). When a more realistic load is applied in these studies, a better understanding is obtained from the load-carrying reserve of the structure. This should be an ongoing research topic in the future.
References


Kotisalo, K., Kujala, P., 1999a. Ice load measurements onboard MT Uikku, Measurements results from ARCDDEV-voyage to Ob-estuary, April-May 1998, Report from WP8 of ARCDDEV project supported by the EC Transport programme, Espoo, Finland.


Lensu, M., 2002b. Short term prediction of ice loads experienced by ice going ships, Helsinki University of Technology, Ship Laboratory, Report M-269, Espoo, Finland.


Ralph, F., Jordaan, I., 2013. Probabilistic methodology for design of Arctic ships. 32nd Int. Conf. on Ocean, Offshore and Arctic Engineering, Nantes, France, June 9-14, 2013.


Schade, H., 1951. The effective breadth of stiffened plating under bending loads. Trans SNAME 1951:59:403-20


Suominen, M., Kujala, P., Kotilainen, M., 2015. The encountered extreme events and predicted maximum ice-induced loads on the ship hull in the Southern Ocean. 34th Int. Conf. on Ocean, Offshore and Arctic Engineering, St. John’s, Newfoundland, Canada, May 31-June 5, 2015.


The design of safe structures requires knowledge about the load-carrying capacity of the structure and the loads encountered by the structure. As several factors affect the ice breaking process, the process is complex and difficult to define. Thus, long-term measurements are required in order to estimate the variability of the loading reliably. However, the uncertainty related to these measurements has not received a proper attention.

This work focuses on the uncertainty and variation in the ice-induced load measurements on the hull of a ship when the measurements are based on shear strain measurements. The work presents an analytical model, which can be applied to estimate the uncertainty related to the measurements. Furthermore, the magnitude and statistics of the loading on a frame as a function of the load length is studied. The work applies the ice-induced load measurements during the ice trials of S.A. Agulhas II in the Baltic Sea in the winter of 2012.