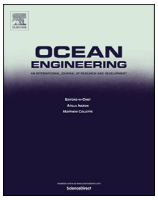
Ocean Engineering 144 (2017) 327–339

Contents lists available at ScienceDirect

Ocean Engineering

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



The effect of the extension of the instrumentation on the measured ice-induced load on a ship hull

Mikko Suominen [*], Pentti Kujala, Jani Romanoff, Heikki Remes

Aalto University, School of Engineering, Department of Mechanical Engineering, PO Box 15300, FI-00076, Aalto, Finland

ARTICLE INFO

Keywords:
Ice load
Full-scale
Uncertainty in measurements
Load length
The extension of the instrumentation

ABSTRACT

Due to the complexity of the ice-structure interaction, the knowledge about the ice-induced loads on a ship hull has been gained from full-scale measurements. As the instrumentation of the hull for the measurements is expensive, the extension is concerned at the planning phase. However, a narrow instrumentation can cause an error in the measurements, as the response of the adjacent frames with respect to the observed frame is not known. Thus, this paper studies the differences between loads measured from one or several frames on board S.A. Agulhas II. The difference results from the ability of the structure to transport loading internally. The results show that when the loads affect only an individual frame, the instrumentations give similar results. However, the difference increases with the load length and the loading that is determined can be 15% higher for one frame instrumentation for a structure similar to the aft shoulder of S.A. Agulhas II. Furthermore, the difference in the mean value and standard deviation of the measurement time histories can be up to 10%. The study presents a new efficient method to obtain a rough estimate of the possible difference in the measured results between extensive and narrow instrumentation.

1. Introduction

Maritime transportation offers an efficient way to transport large quantities of goods and raw material. As some of the routes lie at higher latitudes, e.g. in the Great Lakes, the Baltic Sea, and the Arctic, the ships operating in these areas have to be capable of operating in ice conditions. In order to secure their safety, the structure of the ships has to be designed for these conditions. From the structural design point of view, the magnitude and extent of the external loading are of interest. Ice-induced loading and structural response under the loading have been studied numerically (see e.g. Su et al., 2011), with laboratory experiments (see e.g. Kim and Quinton, 2016) and full-scale measurements (see e.g. Ehlers et al., 2015). However, the ice-breaking process is fairly complex due to the variation in the ice conditions (e.g. strength, thickness, first- or multi-year ice), ship operations (e.g. manoeuvres), and in the location and area of the contact (e.g. ship shoulder, mid-ship). The benefit of full-scale measurements in comparison to the numerical methods and experiments is that all the variations are embedded in the measurements. Therefore, knowledge obtained from full-scale measurements has crucial importance.

Different techniques to measure full-scale ice loads on a ship hull have been utilized. As the ice pressure on a small area can be significant – see e.g. Sanderson (1988) and Taylor et al. (2010) – external foils do not last long outside the hull; see e.g. the measurements by Riska et al. (1990) with a polyvinylidene difluoride (PVDF) film. Alternative ways of measuring the pressure pattern outside the hull have been developed that employ additional construction that can survive the ice contact (Gagnon, 2008). However, these types of solutions can alter the stiffness of the structure, which affects the load-carrying mechanism of the hull structure and possibly also the load magnitude. Thus, the ice-induced loading is commonly measured by measuring the shear strain difference at the ends of the transverse frames, as it is assumed that the load transfer is mainly due to shear along this frame (see e.g. Riska et al., 1983; Kujala and Vuorio, 1986; St. John et al., 1994; Ritch et al., 2008; Suominen et al., 2013). In these type of measurements, the loading is determined from the strain-force relation.

Although all the variations are embedded in the full-scale measurements, the measurements contain uncertainty related to the determination of the force from the measured strain. The uncertainty arises from the assumptions on the loading conditions in the determination of the strain-force relation and from the extension of the instrumentation. The ice-frames are connected to the adjacent frames via typically relatively thick hull plating. As the plates are thick, the plates also transfer the loads imposed on a single frame directly to adjacent frames, but also

---

[*] Corresponding author.
E-mail address: mikko.suominen@aalto.fi (M. Suominen).

https://doi.org/10.1016/j.oceaneng.2017.09.056
Received 21 March 2017; Received in revised form 22 August 2017; Accepted 24 September 2017

to the supporting web-frames directly. 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; Ship Structure Committee, 1990; Ralph et al., 2003; Suominen et al., 2017). Commonly, the influence matrix is defined by employing finite element analysis (FEA). The extent of the instrumentation in 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; Suominen et al., 2013). In a case single frame is instrumented, the influence coefficient matrix cannot be applied and uncertainty is increased.

Although the internal load distribution between the frames has been studied, the knowledge has not been applied to the thorough estimation of the uncertainty of the full-scale measurements. Earlier studies have estimated the effect of the calibration load length – 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; Ship Structure Committee, 1990). Although these studies provided rough estimates of the uncertainty, the uncertainty analysis has not been applied extensively to full-scale measurements. When only one frame is instrumented, the possible overestimation or underestimation of the external loading depends on the ability of the structure to distribute the load to the adjacent frames and on the length of the external loading. 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; Suominen et al., 2017). Suominen et al. (2017) and Newmark (1938) discussed that the ratio between the frame and plating stiffness affects the ability of the structure to distribute loading to the adjacent frames.

Thus, the aim of this study is to determine 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. In addition, the effect of the instrumentation on the statistical parameters of the measured ice load history, specifically the mean value, standard deviation and the coefficient of variation, will be analyzed. Chapter 2 describes the load transfer between frames. Chapters 3 and 4 study the sensitivity of the measurements on the extension of the instrumentation employing full-scale measurements on board polar supply and research vessel (PSRV) S.A. Agulhas II. The instrumented frames on board S.A. Agulhas II are considered to be instrumented separately and jointly. Finally, Chapter 4.5 presents a novel method to estimate the difference between an extensive and a narrow instrumentation.

2. Description of the load transfer between frames

In the ice breaking process, the bending failure of the ice sheet forms a cusp-like breaking pattern; see Fig. 1. Due to the pattern, the hull of the ship is partly in contact with ice and the location and length of the loading varies as the ship proceeds in the ice sheet. In the process, the ice induces a line-like pressure pattern at the contact locations for first-year ice (see e.g. Riska et al., 1990, Fig. 1) and high-pressure zones for thicker multi-year ice (see e.g. Jordaan, 2001; Taylor and Richard, 2014). The loading is transported and carried by the frames supporting the plate. The load causes a shear force on the frames; see Fig. 1. The loaded frame carries the majority of the loading. However, a part of the loading is transported by the plating to the adjacent frames and a part to the stiffer structure supporting the frames, such as stringers.

In the case of limited instrumentation, e.g. with one frame instrumented, the sensitivity of the measurement results on the length of the external loading is directly affected by the ability of the structure to transfer loading internally, as the response and conditions on the adjacent uninstrumented frames are not known. As discussed by e.g. Suominen et al. (2017) and Newmark (1938), the ratio of the frame and plating stiffness affects the amount of loading the loaded frame carries. Thus, this chapter presents the amount of load possibly transferred between the frames, which reflects the possible error related to the extension of the instrumentation in the measurements. Finite element (FE) and analytical methods are used for this.

2.1. Finite element analysis of the stiffened panels

The FE models implemented to study the load transfer are frame systems that consist of nine frames in total. Fig. 2 presents a sketch of the structure employed in the study cut in the line of symmetry, LS. The frame systems are simplifications of real structures. However, the systems are considered to represent the real side structure under ice loading with acceptable accuracy. The mesh size is 0.01 m. Pre- and post-processing were carried out with Femap and the linear-elastic solution with NX Nastran (version 10.3.1). In total 45 FE models were constructed, in which the frame spacing, s, the web height, h_W, the frame thickness, t_W, and the plate thickness, t_P, were varied; see Fig. 2 and Table 1. The length of the frame, L, is 1.5 m in each case. The selection of the cases was made starting from typical design spaces for ice-going vessels and then expanding from those. A 10-kN point load was applied at the middle of the model–see Fig. 2–for each structural configuration presented in Table 1. Clamped boundary conditions were applied for each structure at the outer edges of the plating and at the end of the

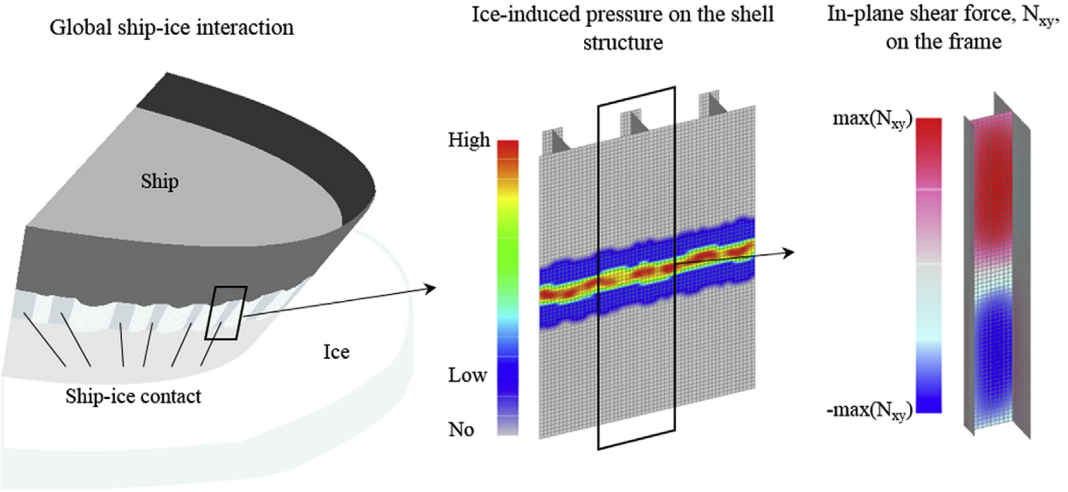


Fig. 1. Schematic illustration of the global ship-ice interaction, the ice-induced pressure on the shell structure and the resulting in-plane shear force, N_{xy}, on the frame.