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Load carrying capacity of ice-strengthened frames under idealized ice load and boundary conditions

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ABSTRACT

Overload response of the stiffening frames in ship side structure due to ice loading is an important design consideration for ships operating in ice infested waters. By overload, we mean loads that are larger than assumed by the rules. Therefore, the response of ice strengthened grillage frames is investigated under a range of idealized rectangular pressure patches and by assuming different boundary conditions for the structural units. A flat, representative grillage of an ice-strengthened ship is considered and analysed using non-linear Finite Element Method. The response of the grillage frames is compared with the isolated frame response. Two frame types are considered: flatbars and L-frames. Finite element simulations revealed that patch length has strong effect on the frame deformation mode. The key characteristic that differentiates the response under shorter and longer patches is the longitudinal membrane stretching of the shell plating. Longer patches tend to suppress this deformation mode that leads to similar frame behaviour observed in isolated frame analysis. It is further shown that overload capacity of grillage frames reduces with increasing patch length to levels observed in isolated frame analysis. Analysis of plastic strain development in the frames and plating revealed that plastic strain localized faster in frames, but shell plating is more sensitive to patch height variations. This renders frames more susceptible to fracture than plating. Finally, the local failure mechanisms of the L-frames tend to diminish the load sharing capability and so negatively affects the overload behaviour.

1. Introduction

In Finland, about 90% of export and 80% of import are transported by sea using ships [1]. Since the sea is freezing annually in the region (Bay of Bothnia and Gulf of Finland) the ice loads must be accounted for in the design of ship structures. Therefore, ships operating in the region during the season must comply with the Finnish-Swedish Ice Class Rules (FSICR [2]), which are considered as "industry standard" for designing ships for first-year ice environments, see Ref. [3]. According to Riska and Kämäräinen [3], the design point in current rules is reaching yield at least once per winter on shell plating or supporting secondary frames. In contrast, ships operating in multi-year ice conditions must comply with IACS polar rules [4], which allow observable plastic deformations to develop in the structure due to ice load, but do not specify any measurable permanent deformations. The principle difference between elastic and plastic design methodology is that for the same loading scenario and steel material behaviour, plastic design methodology leads to reduced scantlings compared with elastic design due to the formation of plastic mechanism.

Reduction of scantlings is important considering the increasing demand for energy and operational efficiency. Therefore, over-dimensioning of ice-going ships should be avoided, because these ships compete with open-water ships during the open-water season

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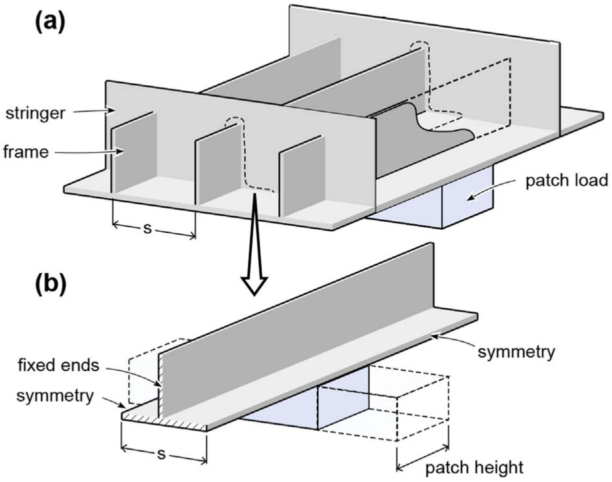

Fig. 1. (a) Frame as part of the grillage and the (b) isolated frame modelling approach.

[5]. This leads to a relevant question from design and economic perspective, which in the context of Arctic shipping can be formulated as in Ref. [6]: "*How low the ice class – and how close the ship can be to open water ship – to make the voyage without undue risks*". The question provides the incentive to explore the plastic design criteria as indicated in Fig. 1 since plastic behaviour of structures has been recognized to be essential in a rational ship design method in recent years, e.g. see the discussion in Refs. [7,8]. However, plastic deformations, as opposed to elastic deformations, are associated with a permanent set and non-linear structural response. The intertwining effects between load, the degradation of material due to corrosion, non-linear material behaviour, and consequent frame response in the grillage, up to the point of structural limit states are relatively unexplored territory in the context of ice strengthened ship structures. As discussed by Wang et al. [8,9] these challenging aspects are also the main cause for unclear safety margin in ice strengthening design standards.

To fill this gap, the paper provides insight into the ice-induced overload response and plastic capacity of frames in transversally stiffened grillage. By overload, we mean loads that are larger than assumed by the rules. The behaviour of ice strengthened structures under overload situations has been studied using Finite Element Method as early as 1980, see Ref. [10]. More recently, Daley et al. [11] provided the relevant insight into the overload response of isolated flat-bar frames under ice loads (Fig. 2(b)). By consideration of a wide range of frames with different web height to thickness ratio they determined the critical slenderness threshold, which exceedance leads to unstable web buckling as opposed to more favourable stable, buckling-free bending of the frame. However, compared with the isolated frame where deformations are constrained with idealistic boundary conditions, the frame in grillage (Fig. 2(a)) can behave quite differently depending on the load re-distribution in the grillage due to plate bending and the actual boundary conditions at the location of web-frames. Furthermore, these works consider plastification and collapse of a frame, but do not attempt to analyse the fracture limit state due to ice induced pressure loads. Therefore, the objective of the current work is to shed light on the limit states with respect to buckling and fracture of ice strengthened ship structures when frames are modelled as part of the grillage compared with isolated modelling approach.

Considered grillage is a representative of IA Super class ship and consists of hull plating, web frames, stringers and stiffening frames. To simplify the analysis on failure modes, initial curvature of the plating is neglected. The IA Super ice class provides a

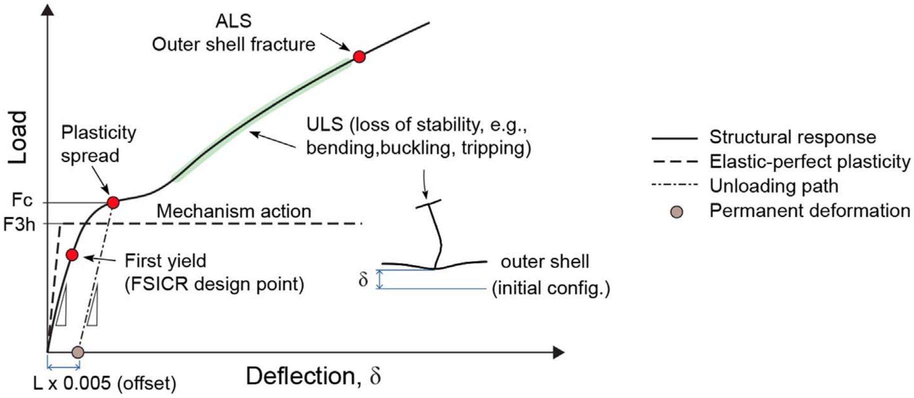

Fig. 2. Example of load-deflection curves for frames together with definitions used in this paper. Permanent deformation refers to inelastic, plastic deformation that is not recoverable and is measured on the outer shell at the location of frame.