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# On the resistance to penetration of stiffened plates, Part I – Experiments

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ABSTRACT

The paper deals with hull damage in ships which are subjected to grounding actions. A ship is assumed to settle vertically on a rock. It is further assumed that contact actions are local and restricted to one plate section. The scenario is analyzed by conducting a series of panel indentation experiments. Various configurations of stiffened panels are loaded laterally by a cone shaped indenter until fracture occurs. The specimen dimensions represent a 1:3 scale of the dimensions found in medium sized tankers. Naturally, because damaged hull and cargo tanks may have severe environmental consequences, e.g. as exemplified by high profiled grounding accidents such as the *Exxon Valdez* grounding which lead to the discharge of nearly 240,000 barrels of oil, focus is on the plastic deformation and fracture resistance of the panel.

This is Part I of a two part companion paper. This paper reports observations from the experiments. Part II–Numerical Analysis deals with the numerical simulations of the same tests. Although, the attention is primarily focused on ship grounding, the experimental results are of considerable relevance for other types of abnormal actions, e.g. ship–ship collisions, dropped objects on deck structures, and stiffened panels subjected to explosions or ice actions.



## 1. Introduction

The objective of this paper is to study structural failure mechanisms in ships subjected to stranding. The resistance to penetration of the hull plating is of special interest. This is because onset of fracture in the outer hull and in cargo tanks is directly linked to oil spill and compartment flooding. Moreover, onset of fracture results in degraded structural capacity. This is especially the case for structural members such as hull panels which carry loads primarily by membrane action.

This is Part 1 of a two part article. The focus is placed on the indentation resistance of hull panels during ship grounding. This is investigated by means of panel penetration experiments and numerical simulations. In this article the execution and the observations from the penetration experiments are described. Part 2 [1] deals with the numerical reconstruction of the tests.

### 1.1. Background

Ship grounding scenarios can be divided into two sub groups: “stranding” and “powered grounding”. During powered grounding, structural damage is driven by the momentum of the ship, see Simonsen and Hansen [2]. Depending on the topology of the sea floor, the ship may either tear open or slide over ground. In the case of stranding, it is assumed that the ship settles on the sea floor without being subjected to sway or surge motions. Damage of the hull is a consequence of receding tides and wave loads. In this article the attention is devoted to plate damage caused by stranding.

Amdahl and Kavlie [3] have investigated the stranding response of double bottom structures of ships. A series of scaled down double bottom structures was penetrated by a diamond shaped indenter. A similar study is also reported by Wang et al. [4]. In this case the structural damage was investigated for different indenter geometries. The indenters were modeled as cones with a spherical nose. The shape variation was enforced by varying the nose radius and cone spreading angle. Experimental work on grounding is further presented by Rodd and Phillips [5] and Rodd and Sikora [6], respectively. In the latter paper, grounding was imitated by running a model of a double bottom, carried by a 227 ton twin rail car vehicle, over a reinforced concrete model of the sea floor. In this test, structural damage was predominated by tearing of the hull plating and the internal double bottom girder webs. This type of hull damage is often referred to as “raking damage”, and is mostly associated with powered grounding on rocks or knife-like obstacles.

In a sense, the behavior of ship sides subjected to ship collisions is similar to the stranding problem. The structural arrangement of ship sides is often very similar to that of the bottom arrangement. Furthermore, most large ships have bulbous bows, which during collisions may penetrate the side of the struck ship. In many ways,

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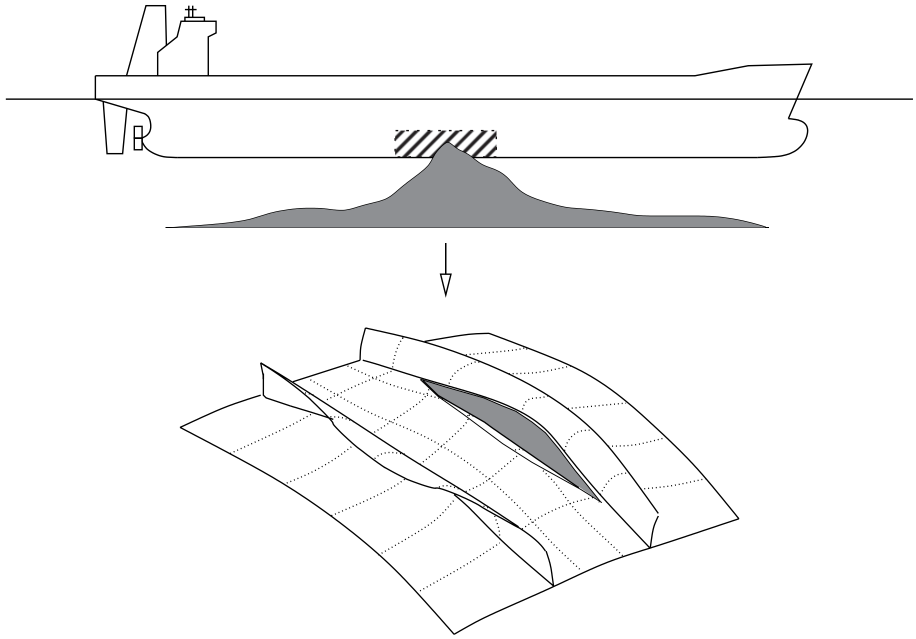

**Fig. 1.** Ship grounding – penetration of a bottom panel.

such bows are similar to the cone indenter applied by Wang et al. [4]. The collision resistance of ship sides has been investigated by Lehmann and Peschmann [7]. A near to full scale ship–ship collision experiment was conducted in cooperation with the Dutch Institute for Applied Physical Research (TNO). Further studies on this and additional collision tests conducted at TNO are reported by Wevers and Vredeveldt [8] and Ehlers et al. [9]. A similar true scale collision study has also been carried out by the Association of Structural Improvement of Shipbuilding in Japan (ASIS) in 1993. This is reported in the 2003 ISSC report [10] (International Ship Structure Congress). As a safety measure to avoid hull penetration, a deformable bow referred to as the buffer bow has been proposed. The behavior of buffer bows is investigated by Yamada [11] through experimental, analytical and numerical studies.

Large scale experiments of ship collision and grounding are expensive and therefore rarely performed. Furthermore, in many cases the sheer size of the components requires tests to be performed dynamically. In addition to uncontrolled strain rate effects, the short time span of these tests makes monitoring difficult. For the purpose of development of analysis methodology, testing of structural members dedicated to a few deformation modes may present a real alternative to full scale testing. This requires less resource and simplifies monitoring. Furthermore, because such tests are often scaled down in size, experiments can conveniently be performed in a quasi-static manner. This approach has been applied extensively by Wierzbicki and Thomas [12], Simonsen and Wierzbicki [13], and Wierzbicki et al. [14] to develop analytical procedures to estimate cutting forces during grounding. It is generally accepted that panels subjected to local impacts are vulnerable to fracture. This is due to the fact that once fracture is initiated, membrane loaded panels have little reserve capacity, e.g. as reported by Simonsen and Lauridsen [15]. The membrane resistance of both steel and aluminum plates has been investigated by Törnqvist [16], in a series of large scale bulge tests, and by Simonsen and Törnqvist [17] when determining the tearing resistance of large metal sheets. The paper focuses on the indentation and the subsequent penetration of hull panels caused by grounding actions. The findings are, however, not restricted to grounding related problems only. They have considerable relevance for other types of accidental loading. This may for instance be panel damage due to: ship–ship collisions, dropped objects on deck structures, and stiffened panels subjected to explosions or ice actions.

### 1.2. Design considerations

The damage to the hull girder during stranding depends on the ship's structural arrangement and the geometry of the sea floor. Ships subjected to grounding on large sea floor obstacles may sustain severe girder web crushing and grillage deformation. This implies enormous contact forces. This creates, in turn, large hull girder bending moments, which, together with a damaged hull cross section, may be critical with respect to hull girder collapse. During stranding on rocks and pinnacles, ships are more likely to sustain local penetration. This may be critical with respect to oil spill and water ingress. In the following study, the latter scenario is assumed to take place. It is assumed that a ship settles on an obstacle where only local contact is established. That is, only the panel section is subjected to deformations. Longitudinal and transverse girders remain undamaged and act as rigid frames. The situation is illustrated in Fig. 1.

**Table 1**
Test component configurations. The panel denotations correspond with component type and the number of stiffeners.

| Component | Number of stiffeners | Stiffener type |
|---|---|---|
| US | none | – |
| 1-FB | one | flat bar (FB) |
| 1-HP | one | bulb (HP) |
| 2-FB | two | flat bar (FB) |
| 2-HP | two | bulb (HP) |