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Experimental and numerical analysis of the crushing behaviour of stiffened web girders

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ABSTRACT

The paper presents experiments and finite element simulations of small-scale stiffened web girders subjected to local in-plane loads, in order to examine their crushing deformations and energy absorbing mechanisms. The specimens, scaled from a tanker bottom floor, are limited by one span between the longitudinal girders and the inner and outer bottom plates. Three small-scale specimens are designed, one unstiffened web girder and two vertically stiffened web girders, in order to compare the influence of the vertical stiffeners on the structural deformation and response of stiffened web girders. This investigation provides practical information to evaluate grounding scenarios where ship bottom floor sustains local penetration. Moreover, it should have relevance to evaluate the extent of structural damage within stiffened decks during side or bow collision accidents. The experimentally recorded force–displacement responses, deformation processes and permanent deformations show good agreement with the simulations performed by the explicit LS-DYNA finite element solver. The numerical analysis discusses some aspects of particular relevance to the behaviour of ship structures subjected to accidental loads. In particular, some comments are offered on the material plasticity and fracture, the importance of specifying the precise boundary conditions and the joining details of the structure.

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1. Introduction

In the event of a collision or grounding, the penetration of the ship side or bottom can result in severe economic loss and casualty. The double-hull structure of the collided/stranded ship should dissipate all the incident energy to avoid the rupture of the inner hull. Therefore, design against accidents should be developed to evaluate the resistance of ship double-hull structures during collision and grounding events. In the potential design criteria, one of the key issues is an accurate assessment for the extent of damage in the structural components of the ship side and bottom subjected to impact loadings.

The most important structural components in double side and bottom are stiffened plates and web girders. The strength of stiffened plates [1–3] and unstiffened web girders [4–7] has been studied extensively, thus the present paper concentrates on the assessment of the plastic behaviour of stiffened web girders.

In typical structures of a ship double side and bottom, the web girders are often designed with longitudinal and/or transverse stiffeners. Over 30 years ago, Nagasawa et al. [8] conducted experiments to investigate the crushing resistance of transversely-framed and longitudinally-framed side structures, showing the large influence of the stiffener orientation. For web girders stiffened longitudinally (i.e. the stiffeners are perpendicular to the direction of the incoming striker), the crushing resistance is very close to that of unstiffened web girders [5–7]. On the other hand, the web girders stiffened transversely can suffer larger crushing force during ship side collision since the transverse stiffeners crush axially. The vertically stiffened bottom floors also sustain the same penetration with the transversely stiffened stringers during ship grounding. Therefore, the current paper is mainly concentrated on the crushing resistance of web girders stiffened vertically (i.e. the stiffeners are parallel to the direction of the incoming striker). This investigation has relevance to evaluate the bottom floor in grounding or stranding and the stiffened deck in side or bow collision [4].

1.1. Description of ship grounding scenarios

Ships may experience various groundings over seabed obstacles during their lifetime. The grounding accidents can be divided into drifting and powered grounding scenarios according to the driving energy, i.e. ship kinetic energy versus environmental force such as wind, current, tide and waves [9]. In other words, there are two types of grounding: vertical penetration often referred to as “stranding” and horizontal slide often referred to as “raking”, as shown in Fig. 1. If the ship is struck on the ground caused by pitch

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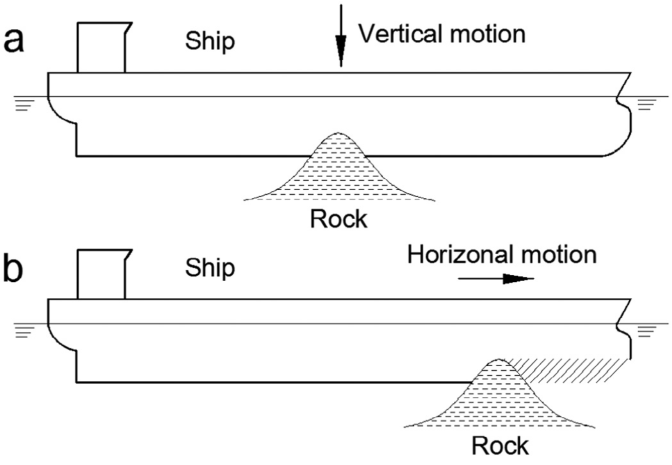

Fig. 1. Grounding scenarios. (a) Vertical penetration. (b) Horizontal slide.

and heave with wave movement (Fig. 1(a)), the bottom structures will be laterally penetrated; if the ship bottom slides over seabed obstacle (Fig. 1(b)), the bottom structures may suffer severe plastic damage and even torn open until absorbing the ship kinetic energy. During an actual grounding, the ship may suffer a combination of these two types of structural damage.

The topologies of seabed obstacle have been outlined in the stranding scenarios by Amdahl et al. [10], namely “rock”, “reef” and “shoal” (see Fig. 2). These different shapes and sizes of obstruction result in various structural damages. The seabed obstacles can also be classified by the character of the ground: soft and hard grounding [9]. Normally, for grounding on soft seabeds, the ship bottom is unlikely to cause severe structural fractures. In fact, the design of ship double-hull structure against collision is conservative, thus the striker is considered as rigid so that the double-hull structure is designed to absorb all impact energy.

The above description is only given to introduce the present experimental–numerical study, which attempts to represent the grounding scenario shown in Fig. 3(a). The double bottom sustains the local vertical penetration of a rigid rock or reef on a bottom floor unit limited by one span between the longitudinal girders and the inner and outer bottom plates.

Table 1
Main particulars of the tanker vessel.

Overall length	Length between perpendiculars	Moulded breadth	Depth	Design draught	Design dead weight
265.00 m	256.50 m	42.50 m	22.00 m	15.00 m	119,320 t

Since the structural pattern of ship bottom floors and decks can be considered as deep web girder stiffened transversely, both structures should behave similarly under the action of quasi-static impact loads [4,5]. In addition, it is reasonable to assume that the deck fails in the folding deformation during the initial collision phase [4]. Thus, the proposed collision scenario manages to describe the inelastic behaviour of ship stiffened decks during side or bow collision scenarios where the stiffeners are crushed axially (see Fig. 3(b)). For reference, the main dimensions of the full-scale prototype are indicated in Table 1.

1.2. *Review and present work*

In order to assess the internal mechanics of ship structures during accidental events, full-scale ship collision and grounding experiments have been performed [11–13]. Such experiments are extremely expensive and thus rarely conducted. Hence, model laboratory tests are the most practical means for investigating the crashworthiness of ship structures. Since the extent of the damage of ship structures can be established by adding up all local contributions of the individual structural components, a series of structural elements have been selected to examine their primary deformation modes and damage mechanics, such as beams [14–19], plates [20–27], stiffened plates [1–3,28–30], unstiffened [4–7,31–34] and stiffened [4,35] web girders. In these references, the experiments on their respective structural components have been used to propose analytical expressions for the energy absorbing mechanics or to validate numerical analyses considering the structural and material characteristics.

Some investigations have been conducted on the crushing resistance of unstiffened web girders under localised in-plane static

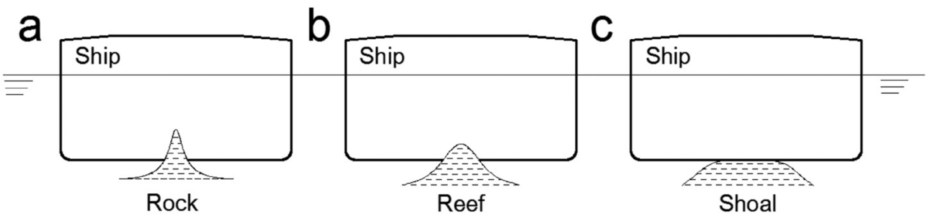

Fig. 2. Topologies of seabed obstacle. (a) Rock. (b) Reef. (c) Shoal. cf. Ref. 10.

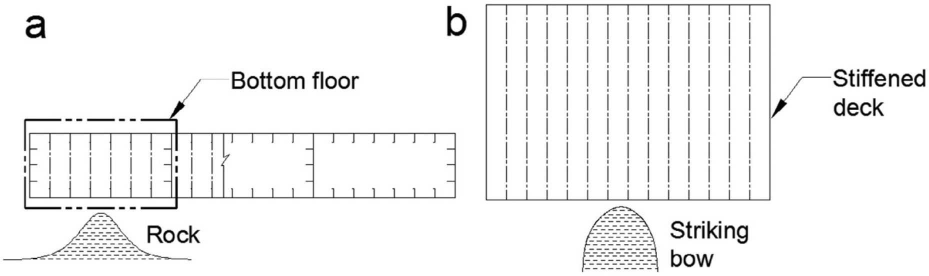

Fig. 3. Impact scenario on the full-scale prototype.

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