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Journal of Ocean Engineering and Science 1 (2016) 167–179

www.elsevier.com/locate/joes

An analytical method to assess the damage and predict the residual strength of a ship in a shoal grounding accident scenario

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Received 22 May 2015; received in revised form 19 August 2015; accepted 18 September 2015
Available online 14 March 2016

Abstract

In this paper, a simplified analytical method used to predict the residual ultimate strength of a ship hull after a shoal grounding accident is proposed. Shoal grounding accidents always lead to severe denting, though not tearing, of the ship bottom structure, which may threaten the global hull girder resistance and result in even worse consequences, such as hull collapse. Here, the degree of damage of the bottom structure is predicted by a series of analytical methods based on the plastic-elastic deformation mechanism. The energy dissipation of a ship bottom structure is obtained from individual components to determine the sliding distance of the seabed obstruction. Then, a new approach to assess the residual strength of the damaged ship subjected to shoal grounding is proposed based on the improved Smith's method. This analytical method is verified by comparing the results of the proposed method and those generated by numerical simulation using the software ABAQUS. The proposed analytical method can be used to assess the safety of a ship with a double bottom during its design phase and predict the residual ultimate strength of a ship after a shoal grounding accident occurs.

Keywords: Shoal grounding; Residual strength; Simplified analytical method; Numerical simulation; Damage analysis.

1. Introduction

Ship grounding over a seabed obstruction may lead to potential consequences, such as significant economic loss and severe environmental pollution, and ultimately may sink the vessel and result in deaths. In the 21st century, although significant progress has been made in improving navigational tools, severe accidents due to grounding still occur periodically. Accidents draw public interest and highlight the importance of making reliable assessments of damaged vessels' hull strength to enhance sailing safety.

During the preliminary design stage or after a grounding accident occurs, it is essential to predict the residual ultimate strength of the damaged ship. To accomplish this task, a more rational design procedure and calculation tools with high efficiency are required. Amdahl [1] proposed the following four items, which are considered elementary in a rational design procedure and are generally followed in this thesis: scenario definition, global and local structural performance calculation, post-accident evaluation and acceptance criteria. The prevailing approaches to analyze the response of ship structures subjected to grounding and to assess the ultimate strength of a ship are typically divided into four categories: empirical methods, model-scale tests, the non-linear finite element method (NLFEM), and simplified analytical methods. The simplified analytical method is an improvement over currently available methods because it is mathematically tractable, has reasonable accuracy, is cost and time effective, and most notably, is superior in providing insight into the governing physical processes.

The deformation mechanics of ship bottom structures involved in grounding accidents vary due to the variety of seabed obstructions. There are three major types of seabed

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http://dx.doi.org/10.1016/j.joes.2016.03.007

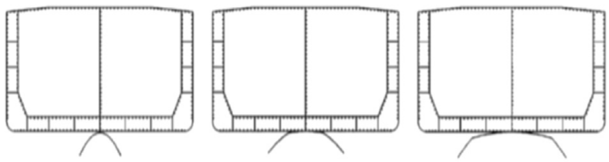

Fig. 1. Seabed topology with reference to bottom sizes: (a) rock; (b) reef; (c) shoal.

indenters as defined by Alsos and Amdahl [2], namely 'rock', 'reef' and 'shoal' (see Fig. 1). A great number of studies have already focused on ship groundings over rock-type seabed obstructions, which primarily tear the bottom plate, resulting in compartment flooding. However, it has been recognized that ship grounding over a flat seabed obstruction with a large contact surface, namely shoal grounding, is more common in practice by Amdahl [1] and Wang ([3], 2002). In this situation, denting rather than tearing is the more likely deformation mode for the bottom plating; as a result, the global hull bending capacity of the ship is at risk as presented by Pedersen [5] and Alsos [6], which may eventually trigger collapse of the hull girder by bending or shearing and cause hazardous consequences as presented by Hong and Amdahl [7]. Thereby, an analysis of the ship ultimate strength after shoal grounding is of crucial importance.

To evaluate the resistance and energy dissipation of a ship's bottom structure during shoal grounding scenarios, Hong and Amdahl [7] proposed an analytical method that assembles various simplified analytical formulae for individual structural components, including a sliding deformation model of the longitudinal girders, denting and crushing models of the transverse members and a denting model of the bottom plating. In the method, the attached stiffeners are taken into account using the smearing thickness approach proposed by Paik and Lee [8]. The method has been challenged by Hu and Amdahl [9], Hu et al. [10] and Yu et al. [11]; it has been found that the smearing thickness method underestimates the role of stiffeners during a shoal grounding accident. In this context, Yu and Hu [11–13] made several predictions on the performance of stiffeners during a ship shoal grounding scenario. These proposed theoretical approaches provide comprehensive descriptions of the deformation modes, energy dissipation and structural resistance of stiffeners attached to the bottom floor plating, longitudinal girder and outer bottom plate. The aforementioned methods have considered all the structural components of the bottom structure that resist structural deformation during shoal grounding. However, the residual strength of the components has not been considered.

The simplified progressive collapse method, also known as the Smith method [15], is a widely known approach to predict the ultimate strength behavior of a ship hull girder. The approach has been shown to provide accurate results by ISSC conference committee [16] and Gordo and Guedes Soares [17]. The Smith method can also assess the residual strength of a damaged hull girder; however, the limited assumptions of the method mean that only a relatively simplistic representation of the damaged area can be modeled. Furthermore, structures damaged from collision or grounding are known to possess residual strengths with a load-carrying capability as presented by Liu et al. [18] and Paik et al. [19]; however, in the conventional Smith method, damaged elements cannot withstand any further load, and thus the method disregards damaged elements in the progressive collapse analysis of a damaged hull girder such as Gordo and Guedes Soares [20] and Wang et al. [3]. Thus, the hull girder deterministic capacity is always underestimated as presented by Wang et al. [4] and Hussein and Guedes Soares [21].

In this paper, a simplified analytical method is proposed to predict the residual ultimate strength of a ship after a shoal grounding accident. Three typical shoal grounding scenarios are defined. A combination of previous studies that have predicted the responses of bottom structures during a shoal grounding accident is validated, and the residual strength of damaged structures is evaluated; certain reasonable assumptions are proposed. In particular, the assumptions of the Smith method are improved. The proposed simplified analytical method is then verified by numerical simulation using ABAQUS code.

2. Response of bottom structures and structural damage analysis

A bottom structure is generally considered to be an assembly of plated structures and stiffeners. Hong and Amdahl [7] proposed a simplified analytical method to predict the responses of three plated structures: transverse floors, longitudinal girders and outer bottom plating. Hereafter, the stiffeners attached to these structures were considered by Yu and Hu [11,13,14]. The seabed obstruction is represented by a rigid indenter with a flat contact surface and a trapezoidal cross-section, and the responses of the bottom can be considered periodic because of the repetitive arrangement of the structural members.

The simplified analytical methods are described briefly below, and a structural damage analysis is proposed.

2.1. Damage analysis of the bottom floor and attached stiffeners

During a shoal grounding scenario, it is observed that the deformation zone of the transverse floor can be divided into two parts (see Fig. 2). The central part, where the breadth is same as that of the indenter, is pushed directly by the indenter. The side part, which deforms simultaneously with the central part, is affected by the indenter indirectly. As a result, the energy dissipated by the transverse floor is calculated by summing the computations of the two parts. The energy dissipated by the collapse of the central part can be expressed as

$$E_{\text{floor,central}} = 4M_{0\_\text{floor}}\left(2.58\frac{H^2}{t} + \left(\frac{\pi}{2}\right)^2 + \pi C\right) \tag{1}$$