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Experimental and numerical investigation of the responses of scaled tanker side double-hull structures laterally punched by conical and knife edge indenters

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ABSTRACT

This paper addresses experimental and finite-element simulation studies on scaled double-hull side structures quasi-statically punched at the mid-span by conical and knife edge indenters to examine their fracture behaviors and energy dissipation mechanisms. The specimen, scaled from a tanker double side, accounts for one span of the stringers in length and two spans of the web frames in width. The experimental results show that a double hull punched by a conical indenter shows much stronger resistance than that of a double hull punched by a knife edge indenter in severe collisions due to a difference in the fracture mode, while the double hull performs better in minor collisions punched by the knife edge indenter due to the deformation mode. In addition, numerical simulations are also carried out for the corresponding scenarios by the explicit LS-DYNA finite element solver. A relatively fine mesh in the contact area is used to capture the fracture initiation and propagation of the two specimens. The resistance-penetration curves and the deformations are compared with those observed in experiments, and these results match well. The numerical analysis discusses some aspects of particular relevance to the response of ship structures suffering accidental loads, including the importance of specifying the modeled welds, the influences of failure criteria, material relations on simulating complex structures, and application of scaling laws in assessing the impact response of full-scale structure.

1. Introduction

Although ship collision avoidance systems and navigation tools have improved considerably in recent years, ship collisions still inevitably occur with increasing tonnage and busier traffic lanes. Once a tanker suffers a serious accident, the penetration of the inner hull involves cargo spillage, and disastrous long-term consequences, particularly environmental pollution that threatens the lives of marine organisms and human beings. Consequently, MARPOL and IMO have successively made it mandatory for tankers to be fitted with double hulls at a certain age [1]. Before rupture of the inner hull, the double hull structure can undergo complex dynamic responses that include crack propagation on the outer hull and a coupling effect between the structural members. Therefore, investigations of the response of double hull structures subjected to collisions are significant for reliable crashworthiness assessment in the pre-design state.

In general, the commonly used approaches to assess the internal mechanics of ship collisions can be categorized as experimental

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methods, numerical simulation methods and simplified analytical methods [2]. Among these approaches, experiments can provide reliable data to verify the other two methods. Previous trials have focused on full-scale collision and grounding experiments with the expectation of simulating real conditions (Netherlands) [3,4]. However, those experiments are extremely expensive. Hence, model tests are usually applied to evaluate the crashworthiness of ship structures. Quasi-static indentation tests are usually applied to investigate the indentation response and damage mode of ship structures. Compared with the low-velocity impact model test, quasi-static indentation testing is relatively easier to conduct and is considered to provide a good reference for low-velocity impact loading situations [5]. Therefore, a host of quasi-static indentation tests were performed to evaluate the deformation and fracture mode of ship structures. For double hull structure punching experiments, a spherical or a conical indenter is usually selected to represent the bulbous bow in a side collision or the seabed obstacle in a stranding scenario [6]. For example, Wang et al. [7] conducted series tests to shed light on the different behaviors of double hulls in a broad spectrum of collision and stranding scenarios. The results revealed that both the indenter size and the penetration location had a significant influence on the reaction force. Paik and Seo [8] utilized double hull punching experiments to validate an efficient method for progressive structural crashworthiness analysis. Karlsson et al. [9] developed four types of experiments, including bulb impact on double hull structures, to establish a reliable and robust FE modeling procedure for ship-ship collision simulations.

In fact, the accidental scenarios a ship may encounter during its sailing life are very uncertain, introducing substantial difficulties for crashworthiness assessments in the pre-design stage. Hence, the establishment of a performance-oriented standard is proposed for assessing the crashworthiness of ships' side structures compared with the majority of rules and regulations [10]. In the cases of ship bow-side collisions, the striking bow profiles that a ship may encounter are diverse. Moreover, the deformation modes and fracture mechanisms of structures impacted by differently shaped indenters can vary greatly. For instance, Jones et al. [11–13] proposed a theoretical method to predict the dimensionless perforation energy for plates struck by various indenter shapes, which illustrates that the indenter shape has a direct bearing on the energy absorption of a plate. Liu et al. [14] reported that the initial fracture of a plate impacted by a spherical indenter or a cylindrical indenter is caused by combined tension and compression or combined tension and shear, respectively. Nevertheless, previous studies have mainly concentrated on the impact responses of single plates. Furthermore, experiments on double hulls punched by various indenter shapes are insufficient. Moreover, as in the approval procedure suggested by Zhang et al. [15], at least two types of striking bow shape should be used to estimate the critical deformation energy during a ship collision. Therefore, the objective of the experiments in this study is to investigate the deformation modes and fracture behaviors of double hull structures punched by different indenters.

The non-linear finite-element method has the ability to predict the large deformation, collapse mode and reaction force of structures subjected to collisions when rationally provided with proper modeling parameters. Therefore, it is widely used to simulate marine structures in many fields of industrial engineering, such as safety calculations, security studies, hazard assessments and structural optimization. Moreover, numerical simulations can be treated as virtual experiments and are currently used extensively to validate simplified analytical methods in many collision and grounding scenarios [16–20]. Compared to model tests, numerical simulations are low cost and repeatable with the help of powerful computers. Furthermore, they can provide detailed information on each structural component, which gives insight into crashworthiness analysis. However, simulation results are sensitive to several factors, including mesh size, failure criteria and the definition of material relationships, as examined in previous benchmark studies [21–23]. Failure prediction using numerical simulation has proven to be a very difficult topic because the effective plastic strain to predict element failure is highly dependent on the element size, and discrepancies can be found in the prediction of ductile fractures in sheet metal when different failure criteria are applied [23]. Therefore, material failure should be validated against experimental tests before performing structural analyses. Moreover, the material relations that can simulate the strain hardening of ductile metal beyond local necking are numerous, and those commonly applied to simulate marine structures subjected to impact load are modified power law formulations [24], combined material relations [25], weighted material relations [26] and Voce material models [27]. Their influence on the simulation results should be discussed extensively. In addition, the boundary conditions simulated in a specific model test should adequately represent the experimental support condition whether in a quasi-static indentation test [5,28,29] or in a low velocity impact test [25,30–32]. Therefore, the focus of the numerical simulation study is defining these influence factors properly, with the aim of developing a robust numerical simulation.

The motivation of this paper is to reveal the damage mode of a scaled double hull punched by conical and knife edge indenters through quasi-static penetration experiments and nonlinear numerical simulations. Another purpose of the model tests is to develop experimental data to validate the numerical method in simulating complex structures. This approach could enable the validated model to be used with confidence to predict the response of full-scale structures under various collision scenarios. The structure of the paper is as follows:

(1) In Section 2, the experimental details are presented, including the design and manufacturing process of the double hull specimen, the material properties of the specimen, the experimental method to obtain the indentation responses and the experimental results.
(2) The numerical simulation is presented in Section 3. The description of the FE models and the material model utilized are presented. Special attention is paid to the boundary condition, the treatment of the modeled welds and the determination of the critical failure strain. Moreover, numerical results are analyzed with the experimental results in terms of the resistance-penetration response, the deformation process and the energy absorbed by each member in each test.
(3) In section 4, several factors that are related with the numerical simulations are discussed, including the modeled welds, mesh resolution, failure criterion, selection of material relation and scaling effects.
(4) Some conclusions are drawn, and suggestions for establishing a robust finite element model are presented in section 5.