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Ship collision and grounding: Scaled experiments and numerical analysis

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ABSTRACT

Scaled models are important in marine engineering since it is prohibitive testing of actual ship size. However, the crashworthiness analysis on marine structures in reduced scale is not an ordinary research topic given the scientific and technical limitations surrounding this type of practice. It is reported here a series of collision tests of marine structures in reduced scale. These experiments are used to validate the subsequent finite element analysis. The scaled shiplike specimens were built from metallic thin-walled structures in a reduced scale of 1:100 taken into account shipbuilding processes analogous to that used in real scale marine structures. The experiments include scaled collision tests of a T cross-section beam, head-on collision of an oil tanker against a rigid wall, ship grounding and collision between two oil tankers. It is discussed the influence of different numerical and experimental aspects inherent to experimental impact tests of marine structures. This includes the mechanical properties of the materials, slight misalignments in test arrangements, failure criteria, weld joints and sloshing effect of ship cargo. These aspects are thoroughly analyzed and discussed here so bringing new insights in the modeling of marine structures subjected to collision events using reduced scale experiments.

1. Introduction

Most catastrophic oil spill ship accidents are due to collision and grounding. Oil tankers represent nearly half of the entire world fleet and they are the maritime segment in which the largest ships are built. These large size vessels are very efficient in transporting oil, but risk a great amount of oil leakage in a possible collision event. In addition to causing ship structure damage and oil spill, it can also lead to degradation of the marine environment, explosions, human losses, blocking of ships traffic and permanent damage to the ship. This global scenario emphasizes the necessity of safety studies in ship collision occurrence.

Recent advances in computational power made practicable finite element modeling of large marine structures subjected to collision. Even though, experimental tests continue to be worldwide performed to validate these numerical models. Discrepancies are found and may be due to limited material characterization [11, 17], failure criteria for base material and weld joints (reviewed by [7]), structural distortions generated during manufacture and assembly processes, structural maintenance level, influence of cargo, hydrodynamic effect of the surrounding water [48] among other aspects. These limitations are difficult to be overcome given their high degree of complexity.

Reduced scale applications are particularly important in marine engineering since experimental tests in actual-scale marine structures demand heavy financial investment, complicated logistic and heavy-duty equipment [44]. Most of the experimental studies about crashworthiness of marine structures deal with collision tests in simplified structures with the aim to represent sections of an actual marine structure. In this respect, Rodd and McCampbell [27] presented experimental tests in 1:5 scale of grounding accidents of ship bottom structures when they are torn by pinnacle rock. Hagiwara et al. [14], Amdahl [2] and Yamada and Endo [46] subjected to crushing tests 1:10, 1:5 and 1:4 scale bulbous bow structures, respectively, to evaluate their structural response under collision. Kuroiwa [18] presented two large-scale experiments, to mimic ship-to-ship collision and grounding events: impact indentation tests and lateral tearing in 1:2 and 1:3 scale web girders. Alsos and Amdahl [3] evaluated experimentally the penetration resistance of ship stiffened plates, in 1:3 scale, when in-plane loaded by a cone shaped indenter. Villavicencio et al. [39] performed drop weight impact tests on 1:10 scale stiffened double plate panel with a rigid knife edge wedge. Recently, Liu and Guedes Soares [20] also carried out low-velocity indentation tests in 1:6 scale stiffened web girders.

Geometrical reduction scales higher than 1:20 are not common when assessing experimentally crashworthiness of marine structures.

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To date, only hydrodynamic ship aspects are traditionally evaluated by miniature models and the experimental reproduction of ship collision accident scenarios in miniature is not a common approach in the marine research community. The complex constructive detailing of a ship structure is one of the principal difficulties to overcome when working in a reduced scale. Thus, Tabri et al. [31] built 1:35 scale ship models, in wood, to simulate a collision between two ships. A rigid bulbous bow, instrumented with a force sensor, was mounted in front of the striking ship. The side of the struck ship was made with polyurethane foam to imitate the deformation behavior of the struck structure. The structural concept used on these miniature ship models makes these experiments limited only for the external dynamics assessment.

It is then the first objective of this research to reproduce experimentally, in 1:100 reduced scale, the structural response and collapse mode of marine structures subjected to collision tests. The second objective is to use these experiments to validate the finite element modeling procedure and analysis. Section 2 introduces the similarity concept used to define the testing parameters and manufacturing details. It follows a complete mechanical characterization of the material used in the reduced models (Section 3). It includes plastic hardening behavior, strain rate sensitivity and structural failure (using different criteria for the structural base material and for the welded joints). In Section 4, the experimental tests and finite element modeling are presented. A basic marine substructure was considered in the first analysis: a T cross-section beam submitted to a mid-span low-velocity indentation. Then, three more complex marine accident scenarios with tanker were also tested: a head-on ship collision test against a rigid structure, a ship grounding accident generated by a sharp rock in the seabed, and a perpendicular collision between two ships in high seas. Finally, in Section 5, discussion of the results and conclusion of the research are given.

2. Reduced scale modeling of experiments

Performing experiments on actual-scale marine structures can be difficult due to the large dimensions and the demanded heavy-duty infrastructure for the mechanical tests. Therefore, it is of great convenience to replace these large structures by reduced-scale structures with analogous response. The technique of reproducing the structural behavior in different scales is called similarity [6]. The laws of similarity for structures have long been developed. Standard similarity factors were generated by dimensional analysis and the assumption of identical materials for the reduced scale and the actual-size structures. The main similarity factors are presented in Table 1, being β the length scaling factor.

Here reduced scale experiments are used to infer the structural response of large-scale marine structures when subjected to impact. A scaling factor of $\beta = 1{:}100 = 0.01$ was chosen for the models taking into account that the complete ship magnitude must be manageable, easy to work and capable of being physically installed in the laboratory. Using this scaling factor, a Suezmax oil tanker of 159,900 DWT, with general dimensions of 254 m length, 46 m width and 24 m height, was considered as a reference structure to be used for the manufacture of all marine model structures resulting in scaled ship of 254 cm in length, 46 cm in width and 24 cm in height. The impacted parts of the model were made with SAE 1008 carbon steel sheet with 0.25 mm thickness, corresponding to real scale steel plates with 25 mm thickness, compatible with shipbuilding plates.

Table 1
Main standard similarity factors.

Symbol	Variable	Similarity factor
L	Length	β
G	Mass	β^3
F	Force	β^2
T	Time	β
$\dot{\varepsilon}$	Strain rate	$1/\beta$
V	Velocity	1
E	Energy	β^3

The mass scaling factor of the ships follows the normal law (β^3), which for scale 1:100 means that the reduced scale model is 10^6 times lighter. The standard scaling factor for the velocity is equal to 1.0, that is, the impact velocity in the reduced scale model is equal to the velocity of the large-scale event to be represented. Strain rate is significantly higher in reduced replicas since it is proportional to $1/\beta$, increasing the material resistance of materials such as carbon steels. Typical strain rates for collision of marine structures range from 5.0 to 400 s^{-1} depending mainly on the structural member [30]. A 1:100 reduce scale model represents a 100 times increase in these strain rate levels. As mentioned in Oshiro and Alves [22, 23], it leads to a distortion in the standard similitude laws. This issue was also addressed by Oshiro and Alves [24].

3. Material model

The SAE 1008 carbon steel 0.25 mm sheet is assumed to be equivalent to Grade A naval steel plates (25 mm thickness) normally used in shipbuilding industry. Here, plastic strain hardening behavior, strain rate sensitivity and material failure are investigated.

3.1. Plastic strain hardening

Measuring plastic strain hardening of a material using standard uniaxial tensile tests is difficult when necking initiates since, in the necking section, the strain field is no longer uniform and an overall strain measurement does not represent the real local plastic behavior. An optimization procedure was used to calibrate the parameters of the plastic strain hardening model based on an experimental uniaxial tensile test at low velocity. The uniaxial tensile test was performed in an Instron universal testing machine, model 3369, at a test velocity of 0.0025 mm/s. Dimensions of the standard dogbone specimen are shown in Fig. 1a. The FE model for calibration was created using quadrilateral 0.5×0.5 mm shell elements. Standard mechanical properties for the elastic behavior of the material and density were used (Table 2). The Voce [40] material model corrected by the strain rate sensitivity using the Cowper–Symonds equation [5], as explained below, was used because it gives a good description of the plastic strain hardening of the material with four material parameters, according to

$$\sigma = \left[k + R_0.\varepsilon_p + R_\infty\left(1 - e^{-b\varepsilon_p}\right)\right]\left[1 + (\dot{\varepsilon}/C)^{1/p}\right] \quad (1)$$

where k is the yield stress evaluated from the experiment. R_0, R_∞ and b are the variables of the Voce material model obtained from the optimization process, ε_p is the equivalent plastic strain, $\dot{\varepsilon}$ is the strain rate and C and p are parameters of the Cowper-Symonds model. Material failure was not taken into account in this optimization procedure, but the strain rate sensitivity was. The resulting material parameters are presented in Table 2.

3.2. Strain rate sensitivity

In general, carbon steel is rather sensitive to strain rates, exhibiting a higher material resistance as the loading rate increases [5]. To take it into account, Cowper–Symonds [9] model is used to correct the material stress-strain curve obtained at quasi-static conditions as shown in Eq. (1). Experimental tests at different loading rates needed to be performed to evaluate the sensitivity of the true stress strain curve to strain rates. These tests were carried out: in a universal testing machine, Instron model 3369, resulting in strain rates from 0.00001 to 0.1 s^{-1}; in a dynamic testing machine, Instron