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Ship collision damage assessment and validation with experiments and numerical simulations

Shengming Zhang[a,1], R. Villavicencio[a,2], L. Zhu[b,*,3], P. Terndrup Pedersen[b,c,4]

[a] Global Technology Centre, Lloyd's Register EMEA, Southampton, SO16 7QF, UK

[b] Key Laboratory of High Performance Ship Technology of Ministry of Education, School of Transportation, Wuhan University of Technology, Wuhan, 430063, PR China

[c] Department of Mechanical Engineering, Technical University of Denmark, DK-2800, Lyngby, Denmark

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ABSTRACT

Closed-form expressions to estimate the energy absorption and damage extent for severe ship collision damages were initially developed in 1999 [1, 2], and further validated with experimental data in 2016 [3]. To gain further confidence for applications within design using the proposed analytical procedure, it is evident that more detailed and comprehensive comparisons and validations with experiments and numerical simulations are necessary. The purpose of the present paper is to use the analytical approach and finite element analyses to study in depth model-scale and full-scale collision tests so that to further quantify key calculation parameters and to verify the capability and accuracy of the proposed analytical method. In total 18 experimental tests and one full-scale collision accident are evaluated. The 18 experimental energy absorption-penetration and collision force-penetration curves, and the associated finite element simulations, are compared with results obtained from the analytical calculations. It can be concluded that the analytical method gives consistently good agreement with all experiments analysed here. Finally, an application of the analytical method is demonstrated by an example where speed restrictions are determined in a port to avoid LNG cargo leakage in an event of an LNG carrier being struck by another ship.

1. Introduction

A ship-ship collision is a major hazard for ship operations. It can result in loss of human lives and severe environmental damages. This has leaded the maritime community to increase the efforts to mitigate the probability and consequences of ship collision accidents. To develop effective rules and procedures to reduce the risk associated with ship-ship collision events, three steps are required [4]:

(1) A procedure to evaluate the probability of ship collision events in specific sea traffic conditions.
(2) Given a ship-ship collision, then a procedure is needed to estimate the energy which will be released for structural damage of the

* Corresponding author.
E-mail address: ZL79111@hotmail.com (L. Zhu).

[1] Member ISSC2009&2015 Committee Ultimate Strength, ISSC2012 Committee Fatigue and Fracture.
[2] Member ISSC2018 Committee Fatigue and Fracture.
[3] Member ISSC1998 Committee Collisions and Grounding, ISSC2018 Committee Design Principles.
[4] Chairman ISSC1988, Member ISSC2006 Committee Collisions and Grounding.

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involved ship structures (External Dynamics).

(3) Knowing the energy to be absorbed by structural damage, a method is then required to estimate the structural damage extent of the ship structures (Internal Mechanics).

The second step (on external dynamics) has been discussed and addressed by the authors in Ref. [5], where an analytical method to estimate the energy released for crushing of structures was validated with results of 58 model tests and two full-scale experiments. For the third step (internal mechanics), various research works have been published, for example [1,6–8]. The determination of the damage extent in ship collision analysis plays a key role in collision assessments [9].

Minorsky [10] proposed an empirical approach to deal with the structural damage back in 1959 and 26 collision cases of full-scale ship accidents were analysed and developed the empirical formula $E = 47.2R + 32.7$ which relates the absorbed energy E (in MJ) to the destroyed material volume R (in m^3). Though the limitations of this approach are recognised, this empirical formula has been widely used by the industry for ship collision and grounding analyses.

Recently, in 2016, Zhang and Pedersen [3] further examined their simplified analytical method, first presented in 1999 [1,2], to estimate the damage extent during collision accidents. The method is based on the relationship between the absorbed energy and the volume of the damaged material, and takes into account the structural arrangements, material properties and damage modes. A large number of experimental tests were compared with calculated results obtained by the analytical method [3]. Good agreement was achieved. However, it was not the strongest validation because the energy predictions were only verified at a given penetration, e.g. usually at the final damage penetration for each collision experiment. Therefore, it is important to verify the energy response as well as the collision force behaviour during the entire impact event, e.g. at any damage penetration, so that to reflect the full picture of the collision assessment and to validate the robustness of the method.

Non-linear finite element analysis (FEA) has become a popular tool in recent years for ship collision studies [11–15]. In these numerical analyses, one of the key issues is to establish a suitable failure criterion as it has significant effects on the results. The rupture criteria are commonly determined through calibration with uniaxial tensile tests where a relation between the element size and the rupture strain can be established. Although significant efforts have been made in this respect, the scatter of the results between finite element analyses using some of the suggested criteria is still quite large, as demonstrated by Storheim et al. [14].

In fact, the determination of the material rupture strain is critical for both finite element and analytical methods. This parameter can be adjusted to get a good agreement with a particular set of experimental results, but on the other hand, the same adjustment cannot guarantee good agreement with other experiments, and consequently, it is one of the biggest challenges for ship collision damage assessments. The friction coefficient between the indenter and laterally impacted structure also influences the response, though its effect is 'less critical' than the effect of the rupture strain. This paper will address this issue in a consistent way.

The present paper reassess the effectiveness of the analytical method [1,2] by comparing its predictions with 18 collision experiments of double hull structures and one full-scale collision accident. The absorbed energy and impact forces are evaluated throughout the entire impact process where the rupture strain and friction coefficient are treated in a consistent manner in the analytical calculations. Finite element simulations for three experimental models are carried out to observe the contribution of friction and the deformation and damage patterns in the collision response.

It can be concluded that the analytical method predicts the entire impact response with sufficient accuracy for all collision cases evaluated here when a common criterion is consistently used to determine the key parameters. Thus, the method is recommended for collision appraisals as that required in Ref. [9].

2. Damaged material volume method

The analysis and observation of actual ship collision damages reveal that there are two main energy absorption mechanisms involved in the internal mechanics of ship collisions: (a) plastic tension deformation, such as indentation and rupture of the shell plating during the collision, and (b) folding and crushing damage mode, such as crushing and folding of webs, decks and bottoms.

Zhang [1] and Pedersen and Zhang [2] developed formulas for the relationship between the absorbed energy and the damaged material volume for the two energy absorption modes:

Energy absorption by the plastic tension damage mode can be calculated from:

$$E_1 = 0.77\varepsilon_f \sigma_0 R_1 \tag{1}$$

where E_1 is the absorbed energy, σ_0 is the flow stress of the material, ε_f is the rupture strain of the material, and R_1 is the material volume of the damaged/ruptured structural members in tension mode. Before rupture of the shell plating, ε_f is replaced with $(x/x_f)\varepsilon_f$ where x is the penetration and x_f is the critical penetration when the shell ruptures.

Energy absorption by the crushing and folding damage mode can be determined from:

$$E_2 = 3.50\left(\frac{t}{b}\right)^{0.67} \sigma_0 R_2 \tag{2}$$

where t is the thickness of the crushed plate, b is the width of the plate in the crushed cross-section, and R_2 is the material volume of the crushed structural members.

The total absorbed energy can be obtained from the summation of the energy absorbed by each damaged structural member: