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Assessment of the strength of double-hull tanker side structures in minor ship collisions

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The paper presents a simplified analytical method to examine the energy absorbing mechanisms of double-hull ship structures subjected to a flat edge indenter. To validate this method, a numerical simulation is conducted on a structural module derived from an experimentally scaled stiffened panel in previous work. The structural module represents one-fifth scaled double-hull tanker side structures, including three frame spacings along the longitudinal direction and two stringer spacings along the vertical direction. The paper provides practical information to estimate the extent of structural damage within double-hull tanker side structures during minor head-on collisions, where the inner hull does not participate in absorbing impact energy. The numerical definition of material nonlinearities for the selected mesh size is validated against previous experimental results. The numerical simulation describes the plastic deformation and material rupture in the double-hull structure and provides detailed information of the energy dissipated by each structural component. The simplified analytical method estimates the relation between the plastic deformation and the crushing force of the double-hull structure, giving a good agreement with the corresponding numerical force–displacement response. Moreover, the analytical method of internal mechanics is combined with a theoretical analysis of external dynamics to evaluate the energy absorption in a ship-to-ship collision. A procedure for assessing the strength of a collided ship is presented on the basis of the experiments of scaled structures.

1. Introduction

The double-hull structure has been widely applied in the design of ship side and bottom. In a collision event, the double hull structure of the collided ship can experience large plastic deformation and fracture. Specifically, oil tankers involved in accidents release crude oil or petroleum products into the sea, resulting in severe economic loss and potential environmental damage [1,2]. In order to prevent oil spills from breached tanks, the rupture of the inner hull should be avoided. Thus, it is necessary to be able to evaluate accurately the impact resistance of ship's double hulls in the preliminary structural design, involving not only the worst case, but also other minor collision events that ships may experience during service [3–5].

In order to assess the internal mechanics of ship structures during accidental events, empirical formulae, simplified analytical methods, finite element simulations and experiments can be used. Among them, experiments can usually provide the most precise and reliable predictions. Generally, scaled collision experiments are the most preferred means for investigating the impact resistance of ship double-hull structures [3,6–8]. As the extent of the damage of ship structures can be established by adding up contributions of all individual structural components, a series of structural elements have been selected to examine their primary deformation modes and damage mechanics, such as beams [9–12], plates [13–18], stiffened plates [5,19–22] and web girders [23–29]. In these references, the experiments on their respective structural components were used to propose analytical expressions for the energy absorbing mechanisms, or to validate numerical analyses considering the structural and material characteristics.

Nowadays, the finite element method is the preferred tool for predicting failures, maximum deformation, or largest loading that can be sustained by a structure, commonly encountered in the analysis of structural crashworthiness in many fields of engineering. For example, complex finite element models of ship structures have been used to calculate the energy absorbed during a collision and the extent of damage due to large in-plane and out-of-plane loadings in the hull structures [30–34]. Generally, the plastic response of struck structures before fracture can be well predicted by finite element simulations that use accurate true material

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relationships and define precise boundary conditions [16,17,34–37]. Recently, the finite element simulations are used to produce virtual experimental data for ship collision scenarios in order to validate simplified analytical methods [38–42]. These simulations are utilised to identify the plastic deformation pattern in ship structures subjected to a rigid indenter. However, the prediction of rupture in the steel structures has not been improved much. Generally, the failure due to material rupture is still not well resolved numerically, because the failure strain is highly dependent on the size of the finite elements and the criteria for initiation of ductile fracture are still not well established within the entire range of fracture modes, including compression, shear and tension. Thus, the material failure defined in the numerical simulations should be validated against the experimental tests before performing structural analyses.

The simplified analytical methods remain the most rapid tools for evaluating the crashworthiness of ship structures, especially during the preliminary design, the risk assessment and the structural optimisation phases. These methods establish the global pattern of deformation by adding up contributions of all individual structural components, being capable of capturing the main features of the mechanical damage. Over 30 years ago various mechanisms of energy dissipation for ship structures subjected to collision loads were identified and described by Amdahl [43]. Afterwards, simple expressions relating the absorbed energy and the destroyed material volume were proposed [26,44]. Recently, simplified analytical methods to assess the energy absorption of ship structures were developed by analysing the plastic mechanism of individual structural members [5,21,22,26–29,45–47]. They reveal the main features of the structural plastic deformation characteristics during the impact.

The most important structural components in the double-hull structure are stiffened panels and web girders. The simplified analytical approach for evaluating the resistance of the stiffened panels [5,21,22] and the web girders [26–29] has been studied extensively. Liu et al. [5] proposed a simplified analytical method to examine the energy absorbing mechanisms of stiffened panels punched by a rigid flat edge indenter, validated against the experimental and numerical results. Moreover, Liu and Guedes Soares [29] presented a simplified analytical method to evaluate the crushing resistance of web girders subjected to local in-plane loads, and they validated it against experimental and numerical crushing force-indentation responses and deformation modes. Generally, the comparison among previously reported simplified methods demonstrates that the proposed new approaches can evaluate better the crushing behaviour of stiffened panels and web girders during the entire deformation process.

The present paper is a continuation of the recent investigations reported by Liu et al. [5] and Liu and Guedes Soares [29]. The simplified method for evaluating the double-hull structure is established by summing the energy dissipated by individual stiffened panels and web girders. The analytical method is validated against numerical simulation of a structural module derived from an experimentally scaled stiffened panel in Refs. [5,34]. The structural module represents a one-fifth scaled double-hull tanker side structure including three frame spacing along the longitudinal direction and two stringer spacing along the vertical direction. The numerical definition used in the actual simulation, especially the definition of material nonlinearities for the selected mesh size, has been validated against the experimental results reported in Ref. [34]. Afterwards, the numerical results of scaled structure are extrapolated to the full-scale prototype according to the elementary scaling principles. It should be mentioned that it is difficult to evaluate accurately the collapse of full-scale ship collision by the finite element simulations since the definitions of material ruptures are not well solved in coarse finite element models [48–50].

The investigated structure is struck at the mid-span by a flat edge indenter. The selection of this type of indenter shape obeys to the recommendation given in Ref. [4] where it is stated that rational models for the bulbous bow should consider a flat tip on the wedge indenter. During service operation, a ship might be struck by another ship which could have a wide shaped bow. The geometry of the indenter strongly influences the plastic deformation and failure mechanisms of the struck ship.

The actual numerical simulation provides detailed information of the plastic deformation and material rupture in the double-hull structure, and manages to describe the energy dissipated by each structural component and their contribution to total energy during the structural deformation process. The simplified method to evaluate the energy absorption of the double-hull structure describes the deformation mechanism and the inner force individually for the stiffened panel and the web girder. Both the structural components dissipate the incident energy through the membrane plastic tension of the structural elongation and the rotation of plastic hinges at the applied load and supports.

The external dynamics and internal mechanics of ship-to-ship collision are mostly treated independently in the analytical methods. Theoretical analyses of the external dynamics have been proposed to evaluate the relationship between the energy released for crushing and the kinetic energy of ships [51–53]. Therefore, the present simplified method of internal mechanics is combined with the theoretical approach of external dynamics to evaluate the energy absorbing mechanisms of double-hull tanker side structures in ship-to-ship collision. The paper provides preliminary design tools to assess the structural damage during collision accidents and thus develops crashworthy designs of double-hull structures. The procedure for assessing the strength of collided ship is summarised as follows.

- *Scaled stiffened panels*. Impact tests are conducted on scaled stiffened panels to validate the material and mesh size defined in the corresponding numerical simulations.
- *Scaled double-hull structures*. The validated definitions of material and mesh size are used in the numerical modelling of scaled double-hull structures, improving the accuracy of numerical simulations.
- *Full-scale double-hull structures*. The numerical results of scaled double-hull structures are extrapolated to the full-scale prototype according to the elementary scaling principles. Or, simplified analytical methods, validated against the numerical results of scaled double-hull structures, are used to rapidly evaluate the impact strength of full-scale prototype.
- *Ship-to-ship collisions*. The analysed strength of full-scale double-hull structures is combined with the external dynamics of ship collisions to evaluate the impact behaviour of struck ship during collision.

2. Finite element model

The numerical simulation attempts to represent the ship collision scenario shown in Fig. 1: a rigid bulbous bow (striking ship) impacts a ship with a double hull (struck ship). Here, the impact event is scaled to be examined in the numerical simulation, following the geometrical dimensions of an experimentally scaled stiffened panel in Refs. [5,34]. Therefore, the material nonlinearities can be accurately defined in the numerical model on the basis of the previous investigations.

It should be clarified that the finite element simulations are difficult to evaluate accurately the ship collisions at full scale [48–50]. Moreover, there are no full-scale collision experiments to validate the numerical results of ship structures. Thus, it is recommended to validate the numerical results of scaled ship structure with