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Analytical method to assess double-hull ship structures subjected to bulbous bow collision

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ABSTRACT

The paper presents simplified analytical methods to assess the plastic deformation and failure of double-hull ship structures subjected to bulbous bow collision. To validate the methods, numerical simulations are conducted on double-hull tanker side structures including three frame spacings along the longitudinal direction and two stringer spacings along the vertical direction. The paper estimates the extent of damage within double-hull ship structures during minor ship-to-ship collision, where the inner hull does not participate in dissipating incident energy. In the analytical methods, the nose shape of striking bulbous bow is simplified as a hemisphere or a cylinder with hemispherical ends. This equivalence is validated against the similar numerical force-displacement responses using the actual bulbous bow and the simplified strikers. The analytical methods derive expressions to estimate the relation between the plastic deformation and the crushing force of the double-hull structures. The onset of fracture in the outer hull is evaluated by a simple formula based on experimental and theoretical analyses. Finally, the probabilistic structural absorbed energy until the rupture of specific struck ship with respect to the displacement of striking ship is assessed according to the statistical data of ship dimensions and the design principles of bulbous bow.

1. Introduction

As sea lanes are getting more congested and ship speeds are becoming much higher, there is an increasing probability that a ship may experience a terrible collision accident during her lifetime. In ship collision and grounding, the penetration of ship side and bottom can result in severe economic loss and potential environmental damage. Over the last two decades, double-hull structures have become an internationally agreed standard for tankers in order to reduce oil spillage in collision accidents. The empirical results indicate that double-hull tankers are associated with smaller amounts of oil spillage than single-hull ones (Yip et al., 2011).

Standards for design against accidents should be developed to evaluate the resistance of ship structures during collision and grounding events (Amdahl et al., 1995). In the potential design criteria, one of the key issues is the accurate assessment for the extent of damage in the ship structures subjected to impact loadings. In order to assess the internal mechanics of struck structures, empirical formulae, simplified analytical methods, finite element simulations and experiments are used.

Nowadays, the finite element method has become a practicable design tool for evaluating the structural plastic deformation and failure in the field of ocean engineering. For example, complex finite element models of ship structures have been used to calculate the energy absorbed during collision and the extent of damage due to large in-plane and out-of-plane loadings in the hull structures (Naar et al., 2002; Ehlers et al., 2008; Alsos et al., 2009; AbuBakar and Dow, 2013; Villavicencio et al., 2014; Korgesaar and Romanoff, 2014; Marinatos and Samuelides, 2015; Liu and Guedes Soares, 2016a). Generally, the plastic response of struck structures before fracture can be well predicted by finite element simulations that use accurate material true stress-strain relationships and define precise boundary conditions (Ehlers et al., 2008; Liu et al., 2013; Villavicencio et al., 2014). Recently, the finite element simulations are used to produce virtual experimental data for ship collision scenarios in order to validate simplified analytical methods (Hong and Amdahl, 2012; Haris and Amdahl, 2013; Yu et al., 2013; Sun et al., 2015). These simulations are utilised to identify the plastic deformation pattern in ship structures subjected to a rigid indenter. However, the evaluation of rupture in the steel structures has not improved much (Calle and Alves, 2015;

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Storheim et al., 2015; Samuelides, 2015). Generally, lacking of experimental tests to validate the numerical results, the ship collision simulations are performed only to propose analytical expressions for energy absorbing mechanisms until fracture.

The simplified analytical methods remain the most rapid tools for evaluating the impact strength of ship structures, especially during the preliminary design, the structural optimisation and the risk assessment. These methods establish the global energy absorbing mechanisms by adding up the contributions of all individual structural components to the total energy. Recently, the analytical methods are developed to evaluate the plastic deformation and energy absorption of structural members, revealing the main features of the structural plastic deformation characteristics during the impact.

The most important structural components of the ship double hulls are designed with plates, stiffened panels and web girders. The analytical methods for evaluating the impact strength of the plates (Wang et al., 1998; Simonsen and Lauridsen, 2000; Lee et al., 2004; Liu et al., 2014), the stiffened panels (Cho and Lee, 2009; Liu et al., 2015a, 2015b) and the web girders (Zhang, 1999; Simonsen and Ocakli, 1999; Hong and Amdahl, 2008; Liu and Guedes Soares, 2015, 2016b) have been studied extensively. Generally, the reported simplified methods can evaluate approximately the impact strength of individual structural components.

The response of complex marine structures has been estimated as the assembly of various simplified analytical formulae for major structural members (Hong and Amdahl, 2012; Yu et al., 2013; Sun et al., 2015). As the material rupture is difficult to be well evaluated in the analytical and numerical analyses of full-scale ship structures, the analytical prediction is mainly limited to the structural plastic deformation. Thus, the simplified methods can only evaluate the minor collision accidents. Although some empirical expressions have been proposed to evaluate the structural damage (Minorsky, 1959; Wierzbicki and Thomas, 1993; Pedersen and Zhang, 2000), the proposed empirical formulae need further validations.

The geometry of striking bow strongly influences the plastic deformation and failure behaviour of struck ship. In the analytical analysis of stiffened panels, the indenter shape is simplified as a wedge with a flat tip (Cho and Lee, 2009; Liu et al., 2015a, 2015b). This simplicity may not describe well the shape of striking bulbous bow. Thus, the simplicity for the shape of striking bow is evaluated carefully in this paper. For the analytical analysis of web girders, the loading of striking bulbous bow is reasonable to be simplified as a local in-plane load since the width of striking bulbous bow is relatively small comparing with the stringer spacing.

In this paper, the numerical simulations evaluate the plastic deformation and failure of a double-hull tanker side structure subjected to an actual bulbous bow. The double-hull structure includes three frame spacings along the longitudinal direction and two stringer spacings along the vertical direction. In the simulations, the nonlinearities of material behaviour for the selected mesh size, especially the true stress-strain curve and the fracture strain, are defined by analytical formulae proposed by Liu et al. (2017). The simulations describe the energy dissipated by each structural component and their contribution to total energy during the structural deformation process.

Four bows with simplified shape, i.e. wedge, trapezoidal prism, hemisphere and cylinder with hemispherical ends, are used to compare with the actual bulbous bow. Based on the simplified shapes of bulbous bow, simplified analytical methods validated against the numerical results are proposed to evaluate the crushing resistance of double-hull structure. These methods describe the deformation mechanism and the inner force individually for the stiffened panel and the web girder. Moreover, the onset of fracture in the outer hull is evaluated by a simple formula based on experimental and theoretical analyses.

The probabilistic dimensions of bulbous bow are established according to the statistical data of ship dimensions and the design guidelines of bulbs. The probabilistic structural absorbed energy until the rupture of specific struck ship with respect to the displacement of striking ship is analysed on the basis of the proposed analytical methods. This paper has two primary objectives. The first is to develop and validate an analytical method to assess rapidly the strength of struck ship structures. The second is to evaluate the probabilistic dimensions of striking ships and to predict probabilistic energy absorption until fracture of outer hull in collision. In addition, a procedure that establishes a connection between the analytical and the probabilistic method is proposed so that to evaluate rapidly and reasonably the impact resistance of ship side structures. The paper also discusses some of the critical issues in the procedure, such as the simplification of the bulb shapes, the selection and validation of diverse analytical formulae, and the probabilistic analysis of the bulb dimensions. It should be mentioned that while various related works have been published in the last decades, it is still difficult to select the most reasonable and appropriate, among them, with the objective of creating an integrated evaluation procedure. Therefore, the present paper aims at solving these difficulties in selecting and connecting the current formulae. Generally, the work provides preliminary design tools to assess the structural damage during collision accidents and thus develops crashworthy designs of double-hull structures.

2. Finite element model

The numerical simulations represent the ship collision scenario shown in Fig. 1. A rigid bulbous bow (striking ship) impacts the mid-span of a double-hull tanker side structure (struck ship). This impact event is evaluated in the numerical simulations, where the double-hull structure is limited by two stringer spacings along the vertical direction and three frame spacings along the longitudinal direction (Fig. 2).

The geometry of the struck structure is sketched in Fig. 3, and the main dimensions of the reference ship are indicated in Table 1. The double-hull structure consists of one outer panel, one inner panel, two web frames and one stringer. Three frame spacings and two stringer spacings are included and their respective span lengths are 4.0 and 4.8 m. The plate thickness of outer panel is 17 mm and its stiffeners are 400 × 14 mm bulb flat profiles; the plate thickness of web frames is 20 mm and their stiffeners are 200 × 20 mm flat bar profiles; the plate thickness of stringer is 12 mm and their stiffeners are 200 × 15 mm flat bar profiles. The height of web frame and stringer is 2.4 m.

The geometry of the bulbous bow is presented in Fig. 4. As the numerical simulations mainly evaluate the plastic response and failure of the outer panel in the double-hull structure, the penetration on the struck structure is less than 2.0 m as demonstrated in the preliminary numerical simulations. This implies that the forward most part of the

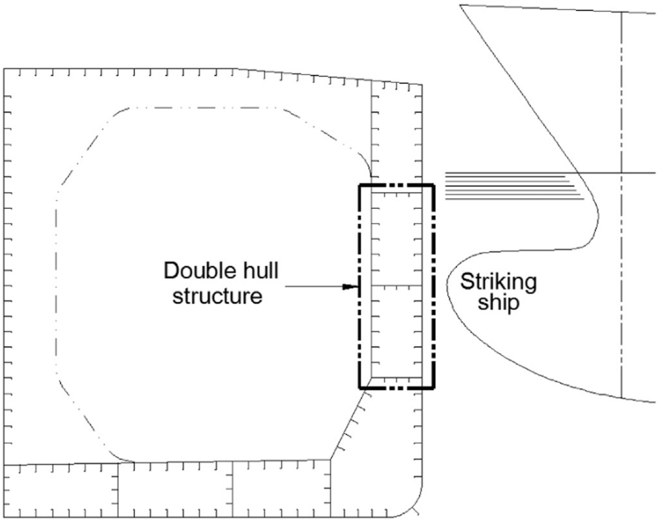

Fig. 1. Impact scenario of ship-to-ship collision.