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Assessment of external dynamics and internal mechanics in ship collisions

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ABSTRACT

The paper compares two methods based on finite element simulations to assess the external dynamics and the internal mechanics in ship collisions. One method treats independently the external dynamics and the internal mechanics (decoupled method), while the other one couples their interaction (coupled method). In the decoupled method, the external dynamics are evaluated by the analytical approach of Pedersen and Zhang (1998), and the internal mechanics are assessed by simulations performed with the LS-DYNA finite element solver. In the coupled method, both the external dynamics and the internal mechanics are evaluated directly by numerical simulations that follow the model of Pill and Tabri (2011). The two methods are compared to determine the differences in predicting the deformation and rupture of the collided ship structures and to assess the relationship between the structural deformation energy of the struck ship and the energy loss of the striking ship. The objective of the paper is to verify whether the decoupled method satisfies the predictions required for design appraisal assessments. The paper also illustrates the influence of the collision angle on the mechanics of ship collisions.

1. Introduction

Standards for design against accidents are developed to evaluate the resistance of ship structures during collision events (Pedersen, 2010; LR, 2016a). Various ship collision simulations have been performed to evaluate the plastic deformation and failure mechanisms of the structures (Paik and Pedersen, 1996; Lehmann and Peschmann, 2002; Ehlers et al., 2008; Pill and Tabri, 2011; Liu and Guedes Soares, 2016a). However, there are no specific standards or guidelines to conduct such simulations. In the design process, the key issues are the accurate prediction of the external dynamics and the internal mechanics of ship collisions, which in general are treated independently (decoupled).

The external dynamics should account for the main fluid forces interacting between the ship and the surrounding water. Minorsky (1959) proposed a theoretical method for the external dynamics to estimate the relationship between the energy released for crushing and the initial kinetic energy of ships, which was limited to central and right angled collision scenarios. To overcome such limitation, Petersen (1982) conducted one of the first time domain simulations capable of treating oblique collisions in two dimensions for arbitrary locations along the ship length. For practical design purposes, Pedersen and Zhang (1998) derived closed-form analytical solutions, based on rigid body mechanics, to estimate the energy released for deforming ship structures impacted at arbitrary locations and angles, which was validated with the simulations of Petersen (1982). Later, Brown (2002) confirmed the accuracy of the method of Pedersen and Zhang (1998) by conducting more advanced and comprehensive time domain simulations. In addition, Tabri et al. (2009a, 2009b) presented theoretical models to predict the consequences of ship-ship collisions when large forces arise due to the sloshing phenomenon in the ballast tanks.

While the external dynamics analyse the total deformation energy absorbed by the ships at the end of the collision, the relationship between this deformation energy and the damage extent of the ships' structure is evaluated by the internal mechanics. To assess the internal mechanics, empirical formulae, simplified analytical methods and finite element simulations have been proposed. Despite the good agreement achieved by some simplified methods (e.g., Pedersen and Zhang, 2000; Zhang and Pedersen, 2017), the finite element method is the preferred design tool for predicting the material failure, the maximum deformation, or the largest loading which can be sustained by a structure.

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Finite element analysis of ship structures is commonly used to estimate the absorbed energy during a collision and the damage extent due to in-plane and out-of-plane loads (e.g., Naar et al., 2002; Ehlers et al., 2008). For ship structures modelled with a relatively large mesh, collision simulations selecting a relatively accurate flow stress curve provide accurate results for pure plastic impact response (AbuBakar and Dow, 2013; Villavicencio et al., 2014; Marinatos and Samuelides, 2015; Liu et al., 2015; Liu and Guedes Soares, 2016b). However, necking and fracture occur over a narrow zone which is much smaller than the side length of the elements, and thus large meshes used in finite element models cannot capture such a local phenomenon. Details for the localisation phenomenon as well as strain concentrations can be found, for example, in Ehlers (2010), Liu et al. (2014), Liu and Guedes Soares (2015) and Dekker and Walters (2017).

Ship collision analysis requires a rather coarse mesh (probably four or five elements between longitudinals, or about ten times the plate thickness) to find equilibrium between practical engineering application and reliable results. Various material failure criteria have been proposed to estimate the critical failure strain as a function of the mesh size (Peschmann, 2001; Törnqvist, 2003; Zhang et al., 2004; Alsos et al., 2008; Liu et al., 2017), but localisation and strain concentration are still difficult to predict accurately.

Comparisons of coupled and decoupled numerical approaches have been conducted by Brown (2002) and Tabri (2012) to investigate the influence of coupling between the ship motions and the strength of ship structures. Brown (2002) concluded that both approaches give similar total deformation energy during the collision, but the deformation energies show large differences in the longitudinal and the transverse components due to the change of the penetration paths in the oblique collisions. Tabri (2012), on the other hand, found that for the coupled approach the initially defined penetration path changes due to the rotation of the ships. Tabri also stated that the decoupled approach manages to evaluate accurately right angled collision scenarios, but for non-symmetric and oblique collisions it predicts deeper penetration in the transverse direction and shorter penetration in longitudinal direction.

Pill and Tabri (2011) proposed a finite element model to simulate global ship-to-ship collision events coupling the external dynamics and the internal mechanics, so that to represent the interaction of the ship motions and the plastic deformation of the structure. While these simulations provided a better description of the collision event, it was mentioned that the input parameters are to be further investigated, and most importantly, validated with experiments.

The coupled and decoupled approaches, reviewed above, only consider three degrees of freedom (3DOF), i.e. the ship motions are restricted in the horizontal water plane. However, 6DOF simulation techniques dealing with the rigid body dynamics have been evaluated by using, for example, the MCOL program. Le Sourne et al. (2001) accounted for the internal mechanics and the external dynamics when used MCOL coupled with LS-DYNA to analyse the global motions of two ships which were considered as rigid bodies under the interaction of the collision forces and the hydrodynamic pressure forces. Le Sourne (2007) coupled the MCOL program with the super-element method, and Le Sourne et al. (2012) coupled it with the upper bound solution. Tabri et al. (2010) also developed a time domain simulation that accounted for 6DOF for both, the striking and the struck ship.

It should be mentioned that 6DOF simulations can be considered a good approximation for analyses of ships colliding with sloping structures, such as a rigid skew-angle plate and/or a ring pontoon in four-legged semisubmersible platforms (Yu and Amdahl, 2016; Yu et al., 2016). However, 3DOF simulations should be enough for ship collisions with ship side structures. In spite of the expected accuracy of the 6DOF 'more complex' simulation techniques, Zhang et al. (2017) concluded that the effect of the roll motion on the energy released is negligible, even for large vertical displacements of the impact point with respect to the vertical centre of gravity. Thus, the omission of motions other than those in the water plane area is justified for ship collision simulations.

Generally, the coupled approaches, as those proposed by Brown (2002), Le Sourne (2007) and Le Sourne et al. (2012), are based on simplifications of the collision forces, and thus the structural damage is difficult to be predicted adequately. The coupled model of Pill and Tabri (2011), based on a common user subroutine in LS-DYNA, shows advantages in the implementation of an adequate material failure criterion together with fine meshes so that to better predict the structural damage and the collision forces. For example, it can be used with advanced strain-rate-dependent fracture criteria, such as RTCL and BWH (Tornqvist, 2003; Alsos et al., 2008).

In this paper, finite element simulations of ship-ship collision that compare a decoupled and a coupled method are presented to analyse the external dynamics and the internal mechanics of ship collisions. The analytical approach of Pedersen and Zhang (1998) is used to estimate the collision energy for the decoupled simulation (referred as displacement controlled simulation), while the coupled simulation (named as dynamic simulation) follows the numerical definitions proposed by Pill and Tabri (2011).

The decoupled and coupled methods are first introduced. Later, a case study for a 'perpendicular' collision (collision angle 90°) using a 4200 TEU (Twenty Equivalent Unit) container ship is presented so that to describe the differences between the two methods for predicting the deformation and rupture of the struck structure. This case study represents the industrial application 'collision assessment of an LNG (as fuel) tank compartment' in which the worst ship-to-ship collision scenario in terms of side shell indentation occurs when the striking bulbous bow impacts the side shell of the struck ship (stationary) between the main supporting members (at the mid-span) (LR, 2016a). Thus, the main objective of the paper is to stablish whether the decoupled method is enough for industry practices, such design appraisal tasks, or more complex dynamics are required.

In addition, the coupled method is used to evaluate the influence of the collision angle on the relationship between the structural deformation energy of the struck ship and the energy loss of the striking ship. This analysis serves not only to describe a more complex collision phenomenon but also to further verify the analytical method of Pedersen and Zhang (1998) as a tool for design and collision risk assessments.

2. Decoupled method

For the decoupled method, an analytical external dynamics analysis is used to estimate the energy loss of the initial kinetic energy to be absorbed for plastic deformation and rupture, and an internal mechanics finite element analysis is used to predict the distribution of the structural damage.

2.1. External dynamics analysis

The analytical expressions proposed by Pedersen and Zhang (1998) are used for this analysis. Since the case study only simulates a perpendicular collision (collision angle = 90°), the mathematical model is simplified and reproduced herein for easy reference.

The collision scenario considers that a rigid striking ship (A) sails at a forward speed V_{ax} and collides with a stationary struck ship (B) at a right angle, as illustrated in Fig. 1. The centre of gravity of the struck ship is assumed at the midship section. The energy released in the X-longitudinal direction can be estimated as

$$E_x = \frac{1}{2}\frac{1}{D_x - \frac{K_x}{K_y}D_y}V_{ax}^2 \tag{1}$$