SHIP COLLISION: A BRIEF SURVEY

Miguel Angel Gonzales Calle, mcallegonzales@gmail.com
Marcilio Alves, maralves@usp.br
Group of Solid Mechanics and Structural Impact, Polytechnic School of the University of Sao Paulo
Av. Prof. Melo Moraes 2231, Cidade Universitária, Butantã, Sao Paulo, Brazil

Abstract. *Ship collisions and grounding continue to occur regardless of continuous efforts to prevent such accidents. Given the recent Brazilian government investments in a new ship fleet, and taking into account the increasing demand for safety at sea and protection of the environment, the consideration of ship collisions is of crucial importance. The purpose of this paper is to present a review of studies about ship collision. This review is focused in researches on the structural aspects involved in a ship collision event, particularly studies about theoretical, experimental and numerical analyses of singular and complex naval structures. Some articles about an energy approach, kinematic systems and probabilistic analysis of the global collision event are also mentioned.*

Keywords*: ship, collision, review*

1. INTRODUCTION

The majority of the most catastrophic accidents of ships occurs due to collision and grounding. These accidents are associated with areas of intense ship traffic and offshore operations such as oil production rigs, Fig. 1. Numerous accidents are caused by human error or failure of the ship, but also by harsh environment conditions. The risk of ship collision had increased in many places on the world together with the growth of the global fleet of ships. Oil tankers represent about 48% of the world fleet and they are the maritime segment in which the largest ships even made are built. These large sizes vessels are very efficient in the transporting oil, but risk a greater amount of oil leakage in a possible collision event. The injury caused by a ship collision accident not only causes oil spill and ship structure damage but also can cause 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 reformulating the security in the entire offshore oil exploration chain, as well as investing in better designs of ships.

Figure 1. Ship collision of Gas Roman and Springok near Singapore coast occurred in 2003.

In Brazil, the consideration of collision-worth ships is of crucial importance to minimize or prevent potential damages to the load and environment, especially given the recent government investments to accelerate the growing of the petroleum sector (PROMEF, Programme for Modernization and Expansion of the Brazilian Fleet) and taking into account the increasing world demand for safety at sea and protection of the environment, especially after the disaster of the Exxon Valdez tanker. The grounding of the tanker Exxon Valdez in 1989 in the coast of Alaska is considered as the largest oil spill catastrophe due to the destruction of hundreds of kilometers of ecosystems in a virgin coastline, leading USA to impose the double hull for tankers. In 1992, The International Maritime Organization (IMO) established the requirement of double hull in the International Convention for the Prevention of Pollution from Ships (MARPOL). Such a new design diminished the structural damage in ship collision incidents, but in some cases it was not enough to prevent critical damages. For this reason, some countries adopted particular measures in tanker ship projects to enhance further ship safety.

The aim of this work is surveying and organizing scientific information regarding the structural behavior of ships in a collision scenario. More than eighty scientific papers about ship collision were reviewed. They were organized in four principal sections: external ship dynamics, internal structural mechanics, finite element modeling of ship collision and experimental test of scaled-model of a ship collision event. The paper layout followed that of other authors (Van Mater *et al.*, 1979; Jones, 1979; Zhang, 1999; Brown, 2002; Wang *et al.*, 2006 and Soares *et al.*, 2009).

2. EXTERNAL SHIP DYNAMICS

In this section, the dynamic behavior of a collision event is analyzed using kinematic system models. The ships are usually considered as rigid bodies and the ship motion is restrained to the plane of the water surface. The aim of this modeling method is to estimative displacements, forces and impulses generated in the two ships as well as the absorbed energy by the ships during the collision.

Minorsky (1959) made the first tentative to analyze the collision dynamics of two ships initially in the context of transporting radioactive materials. His method examines the direct frontal collision on lateral hull of a struck ship, considered as the worst condition by the author. The ships are considered as rigid bodies, the collision is assumed to be completely inelastic and it is assumed linear displacements of both ships, with no rotations. The dissipated energy estimation is based on the conservation of momentum, kinetic energy and inelastic work. An added mass linked to the struck ship to include the hydrodynamic effect was estimated in 40% of the struck ship mass. Later, Petersen (1982) includes the hydrodynamics forces acting during the horizontal motion of the striking ship by accomplishing added masses and damping in each section of the hull. The collision contact, reaction force and structural deformation, was modeled using non-linear springs, Fig. 2.

Hutchison (1986) developed a generalized form of the Minorsky method that includes all the degrees of freedom for plane movements of the ship: surge, sway and yaw. Ships are modeled as rigid bodies and the hydrodynamic force is taken into account inserting added masses for surge and sway motion as well as an added inertia for rotational motion of the striking and struck ships. The mass terms are developed in matrix form. The kinetic energy and momentum of the ships are determined from the resultant velocities and mass matrix. However, this model assumes that, after the inelastic collision, both ships move together as a single body. Some years later, Pedersen and Zhang (1998) and Zhang (1999) also developed similar generalized formulations for the external dynamics collision of two ships, a ship with a floating log, a ship with a rigid wall and a ship with an offshore structure. Their mathematical models include also friction at the contact point so sliding motion is included. Pedersen and Li (2009) analyzed the elastic energy that can be stored in elastic hull vibrations during a ship collision applying the external dynamic formulations seen previously. The elastic vibration of the ship hull is estimated using a simple uniform free beam model to represent the global bending vibration of the struck ship during the ship collision. Only the striking ship is still considered as a rigid body. The elastic energy absorbed by the bending vibration of struck ship can vary from 1 to 6% depending of the characteristics of ships and contact point.

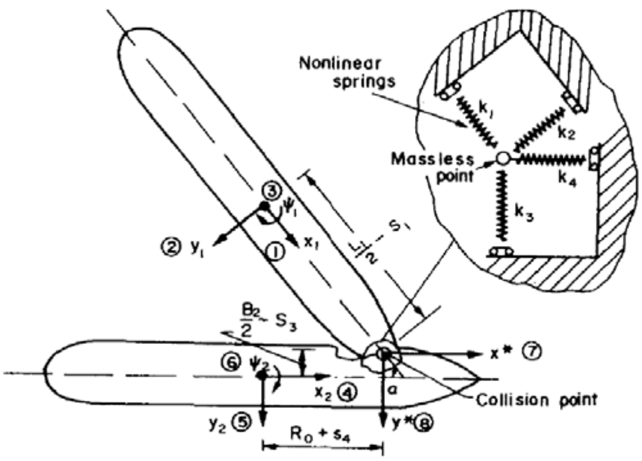


Figure 2. Collision model of Petersen (1982).

These researches presented theoretical formulations to describe the dynamics of both ships. Blok and Dekker (1979) and Blok *et al.* (1983) developed experiments involving scaled model of lateral ship collision against a static protected jetty. This work focused in the analysis of the hydrodynamic mass influence over the collision mode, collision speed and stiffness of the jetty fenders. The scaled ship was a VLCC, carried at full load at velocities between 0.04 to 0.3 m/s. The results showed that the added mass coefficients obtained experimentally are higher and vary depending whether the ship collision is eccentric or not, Fig. 3a. Tabri *et al.* (2008) also developed ship collision experiments involving scaled models. The ship motion and the contact force were measured during the experiments, Fig. 3b. The motion analysis showed that ship motion was nearly linear up to the contact force reached its maximum. During contact, a small angular motion was observed and it increased significantly after contact was lost. The results of scaled model tests, large-scale experiments and an analytical model were compared. The mass ratio resulted to be more significant than the collision velocity and structural response, in the case of symmetry collisions, for the estimation of the dissipated deformation energy. Tabri *et al.* (2009b) validated the scenario of four ship collisions by comparing with experimental results from scaled ship models. Their evaluation involves an external dynamic model of a nonsymmetric ship collisions event considering six degrees of freedom for each ship, an arbitrary impact location and collision angle. The contact force is evaluated by the integral of the surface resistance at the contact interface.

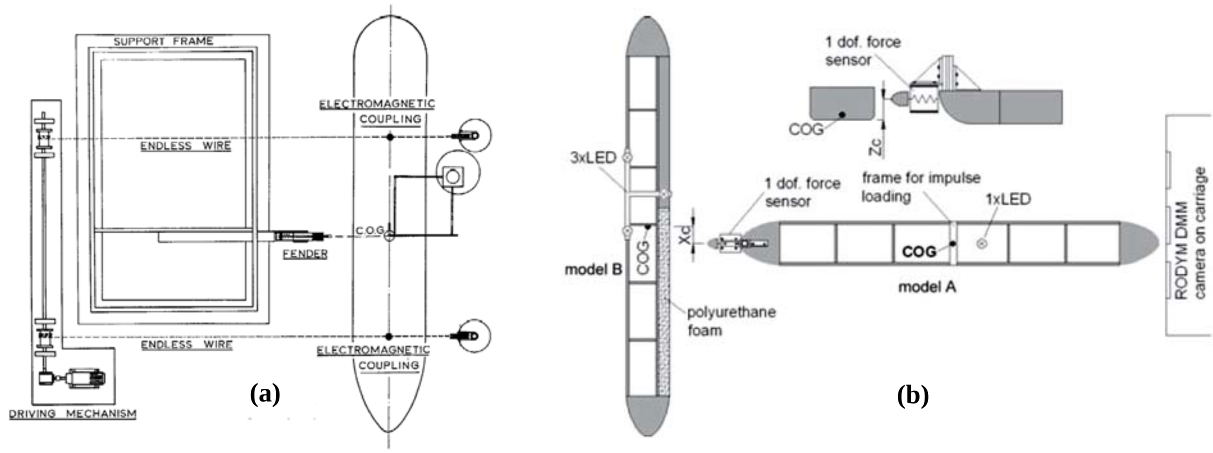


Figure 3. Arrangements of experimental tests on ship collision, (a) Blok *et al.* (1983) and (b) Tabri *et al.* (2008).

Other works used these theoretical formulations to elucidate other ship aspects. For example, Brown and Chen (2002) used these external dynamic formulations to develop probability density functions to describe the damage in struck ship in ship collision. The type of ships and their speeds, collision angle and the striking ship displacement are treated as independent variables. Other parameters are fixed based in the statistics of worldwide ship data. Furthermore, Awal and Islam (2008) investigated the ship capsizing due to collision with another ship in calm water using a dynamic modeling with rigid ships. The mathematical model is validated by comparing the kinetic energy losses obtained by other authors. The maximum amplitude of the roll motion is related to parameters such as striking velocity, coefficient of restitution, collision angle, collision time and vertical position of hitting point to find the survivability associated to the collision event.

Tabri *et al.* (2008, 2009a) studied the effect of the large forces generated by the sloshing in ballast tanks of the struck ship. This sloshing model simulates the liquid cargo using an equivalent mass-spring-damper system. The dynamic generalized model takes into account all aspects of the previous model including the elastic bending of the struck ship and the sloshing model. When compared with experimental tests, the results reveal the significance of the sloshing effect, which stored 32% of the kinetic impact energy instead of transfering it to the ship structure. Also Zhang and Suzuki (2007) analyzed the structural response of a struck liquid cargo-filled tank during a ship collision event to model the fluid-structure interaction in liquid-filled cargo tank. Three different numerical methods were compared: Lagrangian–Eulerian finite elements, Lagrangian finite elements and linear sloshing model, revealing significant differences on the motion and structural response. Lagrangian–Eulerian resulted to be the most efficient method given its relative low computational processing cost.

3. INTERNAL STRUCTURAL MECHANICS

3.1. Empirical formulations

These empirical formulations were developed to allow estimating the deformation energy involved in a ship collision incident. Minorsky (1959) is the most traditional approach to analyze the crashworthiness of a ship collision event. His model presents an empirical formulation derived from data of 26 actual ship to ship collisions, which relates the volume of damaged structural steel to the energy absorbed during the ship collision. His formula is generally considered valid only for high-energy collisions given a poor correlation in low-energy cases. Later, Woisin (1979) extended this formulation to include low-energy collisions and Vaughan (1978) established a new formulation to relate energy with damaged material volume including the area of tearing in his formulation. In the study of Parks and Ammerman (1996) the range of validity of Minorsky model depending on the absorbed energy in a ship collision event is discussed and the inclusion of the basic failure mode of Akita (1972) is recommended. Suzuki *et al.* (2000) also evaluate the efficacy of the Minorsky model by using a simplified rigid plastic analysis of the collision between two tanker ships, one ten times bigger than the other, and demonstrate that Minorsky gives an incorrect estimation of the energy in case of striking or struck ship is much stronger than the other. Finally, Reardon and Sprung (1996) enhanced the formulation of Minorsky and extended for low-energy collisions by adding other 16 actual ship collisions data.

3.2. Simplified methods

Simplified analytical methods are the middle ground between modeling complexity and prediction accuracy. The basic principle of these methods is that both striking and struck ships are decomposed into simple components such as plates, stiffeners, web frames, panels etc. The external dynamics commands the global movements of both ships and the deformation energy absorbed in the collision is estimated by summing all the energies absorbed by each component separately. The first methods are based on plastic membrane tension analysis for low-energy ship collisions before failure, McDermott (1974) and Rosenblatt (1975). They assumed that only struck ship absorbs plastic energy. Reckling (1981, 1983) provides an extension of this method in which striking bow is also allowed to deform. His procedure estimates the stress state of the ship components along the ship collision event. This method only considers perpendicular collision, known contact force, non-rotational ship displacement, additional masses (to represent the hydrodynamic effects); the struck ship was considered as an elastic beam with uniform moment of inertia. The dynamic properties of the involved materials are not considered. This method allowed estimating the critical velocity, i.e. the minimum striking ship velocity, to initiate failure in the target hull. A considerable collision energy absorbed by the striking bow was found, but the energy absorbed by the membrane hull is actually not as significant as supposed. In general, this method gave a rough prediction of a ship collision scenario to understand all the involved variables.

Some works enhanced these methods by analyzing diverse aspects of these procedures. Hence, in the study of Yang and Caldwell (1988), a kinematic method of plasticity to predict the crushing strength of a bow structure in a ship collision event was applied. It is estimated by summing all the energy dissipated by each structural element. The energy absorbed by the axial crumpling of plate elements in the bow structure was the most significant part of all the dissipated collision energy as observed also in experimental tests. An increasing of the mean crushing force due high strain rates effects was detected. Then, Samuelides and Frieze (1989) developed a numerical algorithm in which both dynamic structural and transient hydrodynamic responses during a ship collision event are coupled in the time-step solution. So the dynamic stiffness of the struck ship and the force yielded by the fluid are continuously updated during the simulation. The non-linearities and strain rate sensitivity of the material are also considered and the critical speed of collision was estimated. Egge and Böckenhauer (1991) evaluated the absorbed plastic deformation energy using the ultimate load method for low-energy ship collision analysis. This method divides the affected regions by the collision into their structural components and calculates the resistance of each component by their ultimate load and the buckling theory. The resultant analysis includes the evaluation of critical speed to cause crack in the lateral panel of the struck ship, important to prevent cargo spillage.

Pedersen and Zhang (1999) developed a ship collision simulation employing an analytical method to evaluate the plastic deformation and rupture of the ship structure based on deformation mechanisms coupled with the external dynamic formulations and a collision probability analysis. The entire structure was divided in axial crushing modes L, T and X, which contains its plastic deformation behavior and the non-linear solution, and for the material failure three well-known criteria were reviewed: tensile tearing, transverse shear and energy density failure mode. Then, Pedersen *et al.* (2000) evaluated the ship structure damage using this analytical method. The striking bow is considered as a deformable structure and also as a rigid body. This research demonstrated that only in some cases the assumption of the striking bow as a rigid body is true and also that transversely stiffened bows are significantly softer than the longitudinally stiffened ones. In the same year, Pedersen and Zhang (2000) demonstrated that the assumption of the collision damages, when normalized by the main dimensions of the ship, having the same probability density distributions, in spite of the structural design and ship size, is an error. Actually, normalized collision damage depends on the size of the ship, as verified by actual statistical data. For instance, larger ships or the use of more resistant naval steel shows damage relatively smaller.

Some institutions made efforts to systematize these analytical methods. For that reason, here are also reviewed some numerical codes to couple both external dynamics and internal mechanics analyses of a ship collision event.

The SIMCOL algorithm was originally developed by Crake (1995) and Brown (2002). It uses the time-domain simultaneous analysis of external dynamics and internal mechanics of a ship collision event. Initially, the external dynamics is based in the formulations of Hutchison for three degrees of freedom (1986) and the internal mechanics on the works of Rosenblatt (1975) and Reardon and Sprung (1996). Based on further research, test runs and the need to include a broad range of design and scenario variables, improvements were progressively made by Chen (2000), Brown and Chen (2002), Brown and Sajdak (2004) and Vakkalanka (2000) such as introducing friction forces, lateral deformation of the web frames (considered previously as rigid), the vertical extent of the striking bow as well as analyzing the importance of considering a deformable bow of the striking ship. This software allows analyses with different ship velocities, collision angles and longitudinal position of the struck ship. Thus, Brown *et al.* (2002) joined the SIMCOL software and Monte Carlo optimization method to minimize the collision damage using a sample of 1000 ship collision scenarios. The probability of damage penetration and crashworthiness were estimated.

The DAMAGE collision module is a computational code for a ship tank security program developed at Massachusett Institute of Technology. The fundamentals of this program were developed by Wierzbicki (1983) and Hayduk and Wierzbicki (1984), who established basic solutions to estimate the energy absorption in axial crushing of several plate intersection types called as super-element. Since not all the structures are submitted to axial crushing loads in a ship collision event, Simonsen (1999) introduced this basis by re-discretizing the structure components into super-elements as long as the solution proceeds. This internal mechanics is coupled with external dynamic. Initially, a rigid bow, one degree of freedom system and a right angled collision was considered. Then a deformable bow and both linear and rotational movements of both ships were appended in this software. Nevertheless, perpendicular ship collision continues to be considered as the worst collision case.

The DTU model developed by the Technical University of Denmark also solves the external problem uncoupled from the internal problem and applies the calculated absorbed energy to plastic deformation of the struck ship, similarly to the DAMAGE collision module. The internal mechanics is based on a set of super-elements which represents a structural component: lateral plate deflection and rupture, crushing of structure intersection elements, in-plane crushing and tearing of plates and beam deflection and rupture. The analytical solution of the external dynamics is based on a rigid body mechanism by Pedersen and Zhang (1998, 1999) and the structure deformation is limited to the contact region. Both ships have three degrees of freedom. The collision angle, velocities for both ships and longitudinal location of the struck ship can be adjusted but the bow of the striking vessel is assumed to be rigid. Zhang (1999) validate this method by comparing with experimental data from actual ship collision events and crushing bows experiments, Woisin (1979). Additionally, Lützen (2001) coupled the DTU model with a numerical Monte Carlo simulation for estimating the distribution of damage on the struck ship to propose a damage stability regulation using this approach.

The ALPS/SCOL is a simplified method which uses a coarse-mesh finite element code based in the super-elements concept, called as Idealized Structural Unit Method (ISUM), to analyze the internal mechanics of a ship collision event together but not linked with the external collision dynamics, see Paik and Pedersen (1996) and Paik *et al.* (1999). The mesh of the ship structure is made up by rectangular and triangular units, each unit has a local element coordinate and can describe elastic deformation, yielding and material failure. A rigid bow and added masses to represent the hydrodynamic forces and the sway and yaw movements were considered.

Some works focused in comparative analysis of these numerical codes. Chen (2000) Brown *et al.* (2000, 2002) and Lützen (2001) developed the simulation of the same ship collision event on these four codes presented previously.

Qi *et al.* (2005) developed a systematic study of various theoretical methods for predicting the ultimate hull girder strength of a 300,000 dwt large double hull tanker in a comparative study. The reviewed methods involved a non-linear finite element method (FEM), an improved ISUM, a simplified method (SM) and an advanced analytical method (AM). The results were also compared with the marine standards for oil tankers, which results conservative and in some points limited. This analysis demonstrated that, for a general analysis of ultimate hull girder strength, accurate results can be obtained using these methods ever since the basic assumptions and key points were reasonable solved. Notwithstanding, the implementation of the SM and AM methods resulted to be simpler than the FEM and ISUM.

3.3. Analysis of singular structures

Some studies focused in the analysis of typical single structures utilized in tanker ship construction for a better understanding of their structural behavior. Usual topics of these studies are related to conventional deformation mechanisms observed in ship collision incidents such as deformation of side shell plating, crushing of frames and stringers, crushing of webs, crushing of bulbous bows and so on. Some of these studies were employed to construct the basis of some programs for simplified analysis of ship collision seen previously in Chapter 3.2.

One of the first works about singular structures was made by Wierzbicki (1983) and Hayduk and Wierzbicki (1984) in which simple closed-form solutions to predict the mean crushing force and the energy absorption in axial crushing of plate intersections with X, T and L forms are established, Fig. 4. Lower- and upper-bound solutions for the mean crushing strength were obtained by considering the modes of deformation which takes into account both bending and extensional deformations. Then, Wierzbicki and Suh (1988) presented a theoretical formulation to solve the problem of large plastic deformations and shape distortion of tubes subjected to combined loads: lateral indentation, bending moment and axial force. This analysis showed that the force-deflection curves and absorbed energy of tubes are dependent on the bending moment and axial force at the tube ends (boundary conditions). The formulation was validated by comparing with existing experimental data. Similarly, Wierzbicki and Huang (1991) presented analytical formulae to model the transition from the post-buckling to the post-failure of a thin-walled prismatic column submitted to an axial crushing, which could explain the plastic folding mechanism. Energy and limit analysis methods were used to predict the elastic post-buckling and post-failure response of the column respectively.

Manolakos and Mamalis (1985) developed analytical formulae to predict the structural behavior of a framed shell plate when submitted to minor oblique collisions for any collision angle. For this analysis the shell plate was divided into T-beam units which were subjected to plastic straining up to failure. Therefore, the plate strength and absorbed energy was predicted. The authors confirmed that collision at right angle is the most severe collision condition.

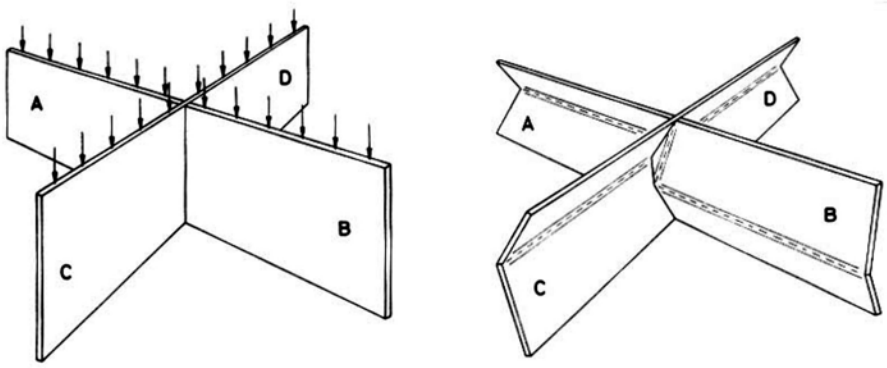


Figure 4. Axial crushing mode of a cruciform plate intersection, Wierzbicki (1983).

Caridis *et al.* (1994) developed a numerical model of thin plates submitted to dynamic loadings and validated by experimental tests. The material model comprised an elastic-viscoplastic non-hardening continuum behavior and the non-linear dynamic response was obtained based on the real-time dynamic relaxation method. The inclusion of the perpendicular-to-plane strain fields in the model and more accurate boundary conditions provided more precision on the results. Moreover, it was found that the inertia effect does not affect the results significantly but the strain rate effect of the material does.

Zhu and Faulkner (1994) proposed a theoretical prediction of the plating damage in offshore structures subjected impact based in the rigid perfectly plastic analysis. Based on the lateral impact tests of the scaled ship model developed by Samuelides (1984), the authors reduced a ship collision event to the indentation of a restrained mild steel plate by a rigid striking mass. An overestimation of the permanent deflection was observed when material elastic behavior and strain hardening sensitivity are neglected. Two years later, Zhu and Faulkner (1996) proposed another theoretical prediction for the same case but considering repeated impacts. On the experimental test, with an identical arrangement, a restrained mild steel plate was collided seventeen times. A theoretically precise prediction was difficult to obtain due to the accumulated error after each impact.

Experimental tests of wedge indentation in lateral of restrained plates revealed a singular failure mode, in which a plate develops two cuts followed by folding ahead of the wedge, so-called concertina tearing mode. Wierzbicki (1995) developed a closed-form solution derived for the plate-resisting force and the length of the folding wave to predict this failure mechanism. The results were compared with small and intermediate scale indentation tests on metal plates, and showed good agreement.

To take into consideration the local inelastic buckling of tubular structural member on a finite element simulation of a ship collision, Skallerud and Amdahl (1998) characterized experimentally the mechanical buckling of tubular specimens, for diverse aspect ratios so these tubular members can be introduced in the model as beam elements with global buckling, local buckling and post-local buckling behaviors.

Simonsen and Ocakli (1999) predicted, using analytical formulae and a rigid-plastic material model, the deep plastic collapse and folding occurrence on a decks and girders of the lateral struck ship structure when penetrated by a ship bow. The evaluation covers large deformations and several folds occurrences but not failure. The load-deflection curves and the deformation modes of decks, stringer decks and deep thin-walled beams were validated by experimental tests. In case of crushing of a deep longitudinal girder with eccentric impact, this analysis predicted well the local response but not the global and for analyzing the deformation of a deck between two transverse sections, the transverse structures can be considered as rigid boundaries.

Kim and Wierzbicki (2001) developed an analytical solution to model the crushing response of thin-walled prismatic column under combined compression and bending loads. Both Shanley nonlinear spring model and the super-beam element concept were used together to model the generalized plastic hinge. This analysis was validated by comparing with a FE modeling of the same crushing tests giving similar force moment curves and failure locus. Mohammed *et al.* (2001) developed non-linear FE simulations of buckling of stiffened plates under combined axial compression with lateral pressure, shear collapse of thin-walled aluminum plate and an axial crushing of a cruciform structure. The results were validated by comparing with experimental tests of other authors and DNV design code. In case of higher pressure loads test, the DNV design code showed to be non-conservative. Amdahl and Stornes (2001) developed the axial crushing tests of six welded aluminium box specimens with different types of transverse and longitudinal stiffening to evaluate the energy dissipation. These tests were numerically reproduced using a FE simulation. These results were used to validate the simulation of the axial crushing of bulbous bow of a high-speed vessel.

Simonsen and Törnqvist (2004) present an experimental-numerical procedure to develop and calibrate macroscopic crack propagation criteria in large-scale shell structures as hull ship using inverse finite element analysis from experimental tests. These experimental tests are based in the crack mode-I for a thick plate under fully plastic condition deformed in both in-plane bending and extension. A large-scale grounding experiment is also simulated and some failure criteria are checked and discussed.

Hong and Amdahl (2007) developed an analytical model to predict the resistance of laterally patch loaded plates in which the plastic yield line theory, the membrane effects and the restriction factor (to take into account the influence of the restrained boundary of a plate with finite dimensions) were considered. The model proposed an alternative collapse mechanism called as double-diamond which showed a reduced resistance and better agreement with the nonlinear finite element results when compared with the conventional roof-top mechanism principally during plastic deformation.

Zhang and Suzuki (2007) and Zhang (2007) analyzed the quasi-static crushing of stiffened square tubes with non-linear finite elements method taking into account large deformations, local folding, internal contact and multi-axial stress fields. Simultaneously, a review of experimental tests and empirical formulations of other authors about the same crushing mechanism were analyzed. New formulae for mean crushing load and equivalent plate thickness for the axial crushing test of square stiffened tubes were proposed.

Hong and Amdahl (2008) developed a theoretical model for the crushing of web girders under localized in-plane loads based in existing simplified methods and observations of the progressive folding process. This model was corroborated with three experimental results found in literature. Variables as the web stiffeners and the dynamic loading were evaluated but they showed no significant influence. On the other hand, the effective crushing factor showed a significant role to predict the mean crushing resistance. The theoretical model show more reliability to reproduce the local progressive folding mechanisms.

Mazzariol *et al.* (2010) scaled a dynamic test, in which a clamped T-section beam is indented transversely by a mass. The influence of the material strain rate sensitivity on the experiments was corrected based on the work of Oshiro and Alves (2009). The analysis of the prototype and the corrected and non-corrected models were enhanced using the finite element modeling, the quasi-static and dynamic mechanical properties were measured and an experimental test of the T-section beam was developed to validate the FE numerical model, Fig. 5. This research demonstrated the importance of considering the dynamic effects when scaling mechanical tests of ship structures.

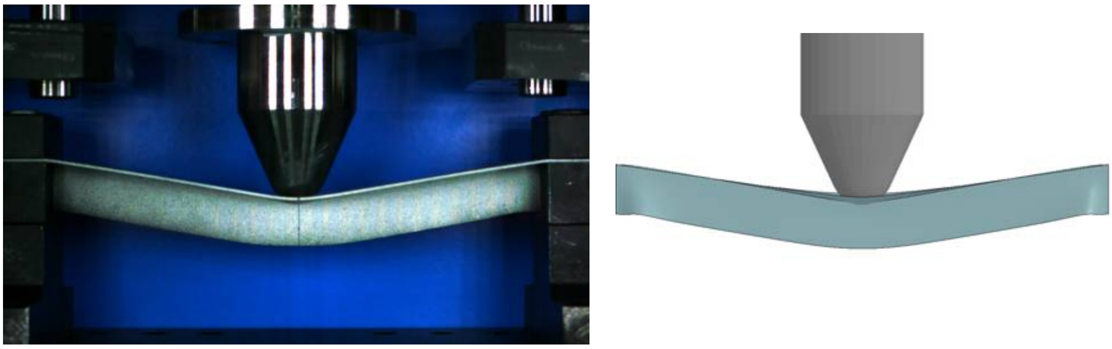


Figure 5. Experimental and numerical dynamic tests of the clamped T-beam, Mazzariol *et al.* (2010).

3.4. Analysis of complex ship structures

Wierzbicki and Driscoll (1995) developed an analytical study of the crushing of ship web girders subjected to local in-plane crushing loads. The web geometry was simplified considering the symmetry of the structural units which compound the entire structure. A simple model of the post-buckling deformation is used to derive an approximate solution for the plastic behavior of the deforming web girder. Experimental tests were executed to corroborate the deformation modes and accuracy of the solution.

Bai *et al.* (1993) presented a finite element modeling of ship hulls under impact loads. Finite elements such as beam-column, stiffened plate and shear panel elements were simplified using the plastic node method approach. Also large deformations, global buckling, local buckling and post-buckling behavior were considered using an effective width concept. Failure criteria for the material were also introduced. The results were corroborated with experimental test of a double hull tanker subjected to a concentrated force in the middle.

Paik and Pedersen (1996) developed a non-linear finite element to model the quasi-static indentation of a double hull based in the idealized structural unit method (ISUM) to validate a ship collision modeling. Thus, the structural webs are modeled using idealized rectangular plate units with equivalent structural response verified by experimental tests of double skin plated structures. Also contact elements and the strain rate sensitive on the material model are considered.

Wang et al. (2000) investigated analytical and experimentally the collision of conical bulbous bows against a double hull structure. For the simplified analytical model, the mechanical response of structural members involves membrane stretching of shell panel, onset of rupture, crack propagation, folding of main members, crushing of intersections of main members and strength reduction of plates with cracks. The double hull structure was modeled as a plate and the bow as a rigid sphere to reproduce the bow penetration in a ship collision event. For the experimental tests were considered five rigid cones with different nose radii and three different locations of penetration, these variables showed to have a strong influence on the behavior of a double hull, Fig. 6a. Some years later, Wu *et al.* (2004) presented the numerical simulation of these tests using the finite element method. The fracture occurs when the equivalent strain reaches its critical value.

Endo *et al.* (2002), Yamada *et al.* (2003) and Yamada (2006) developed experimental tests of the buffer bow crushing, in reduced 1:4 scale, and modeled using a finite element analysis. Both bulbous and blunt-shaped bows were analyzed. The collapse mechanism and the force-displacement curve were compared with the experimental and numerical tests. The experiments were carried out in quasi-static conditions and two kinds of bulbous bows: transverse and longitudinally stiffened bows were axially crushed by rigid board. The buffer bows collapse progressively from top to bottom on axial crushing, Fig. 6b. The use of ring frames stiffeners in the bow structures resulted in a spherical concentric folding mode which maintains a progressive mechanical collapse with force peaks not so high. Oblique collisions of bulbous bow structures were also analyzed by experimental quasi-static tests, Yamada and Endo (2008), with the aim of evaluating the collapse strength and the deformation mechanism. Two kinds of bow structure were tested, a standard longitudinal stiffened bow and a new prototype, a transverse stiffened bow. As consequence, combined bending and localized compressive loads are imposed due to the oblique angle given that the bending mode near the root of the bulb is dominant. Then, some simplified analytical expressions are reviewed by Yamada and Pedersen (2008) to estimate the mean axial crushing forces of stiffened bow structures based on a rigid-perfectly plastic material analysis. The crushing force and total absorbed energy are based on response of intersection and plate unit elements. This analytical modeling is validated by comparing with experimental tests of quasi-static axial crushing of large-scale bulbous bow structures seen previously, Yamada *et al.* (2003). The performance of this method in prediction of the experimental crushing force and absorbed energy is demonstrated.

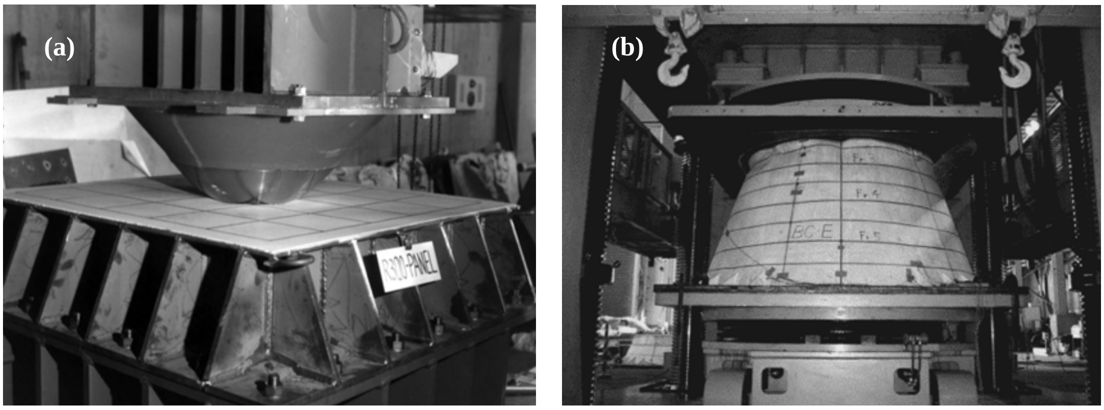


Figure 6. (a) Experimental setup of indentation test on stiffened panel, Wang *et al.* (2000) and (b) Axial crushing of bulbous bow, Yamada *et al.* (2003).

Alsos and Amdahl (2009a, 2009b) analyzed the resistance to penetration of ship stiffened plates when loaded laterally by a cone shaped indenter until fracture occurs. On these papers, the observations from experimental tests, developed in 1:3 scaled specimens, and the numerical modeling of these tests, to investigate the performance of two failure criteria for ductile materials, are reported. The experimental tests showed an unexpected collapse mode of the stiffened panels where the stiffeners tripped and folded to one side, the fractures do not initiate in the stiffeners but next and the increasing the stiffness of the panel reduces the ductility of the whole structure. The numerical modeling showed the efficacy of the Rice-Tracey-Cockcroft-Latham criterion (RTCL) and Bressan-Williams-Hill instability criterion (BWH) to simulate the failure and showed the need to calibrate them applying a fracture scaling law.

4. FINITE ELEMENT MODELING OF SHIP COLLISION

First efforts in modeling a ship collision event using the FEM were done by Lenselink and Thung (1992). They model a ship collision event based in an experimental full-scale ship collision (Vredeveldt and Wevers, 1992). A perpendicular collision was considered. A coarse three-dimensional deformable model was created near the contact area and the remaining part was considered as rigid bodies. The water resistance is modeled by 26 dampers, with a horizontal force as a function of the velocity, attached on the struck ship. As a failure model for the material was not introduced, the simulation agreed with the experiment until cracks initiated. Carlebur (1995) developed a similar model based on the same experimental tests.

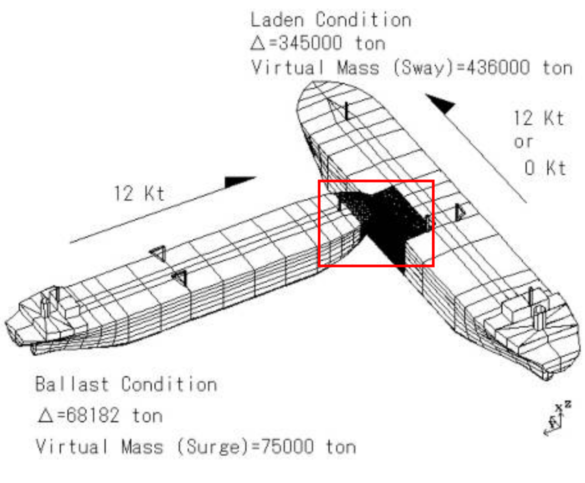
Porter and Ammerman (1995) simulated an entire ship collision event considering four different collision velocities, from 5 to 15 m/s, but not resulting in a hull tearing. The bow geometry of the striking ship was simplified defined as a vertical bow angle. One year later, Ammerman and Daidola (1996) developed a similar FE model of the ship collision event to compare with an analytical routine TSAMC and the Minorsky model. Notwithstanding the efforts, the finite element model absorbed more energy than the other models. The two principal difficulties on this early numerical modeling were a lack of an adequate failure model (mainly when the structures suffer large deformations) and the underestimating of the hydrodynamic forces during the collision. Minorsky (1959) recommend 40% added mass to imitate the hydrodynamic resistance, but other authors, such as Motora (1966), recommend heavier masses up to 150%.

Servis and Samuelides (1999) simulated the collision of the lateral hull of a large Ro-Ro ship by a rigid bulbous bow using the FEM. In order to validate this simulation, two models were created to compare with large-scale experimental collision tests. The first consists in dihedral bow striking against the side of a stiffened deck, and the second, in the collision of a hemisphere bulb against a stiffened panel. The validation shows a good agreement. Also, it was developed a numerical-experimental analysis of the collision of a rigid bulbous bow against two naval vessels, one clamped and the other freely floating to imitate the surrounding water.

Brown *et al.* (2000) presented a summary of diverse procedures developed by recognized scientific institutions to predict the structural response in a ship collision event. These procedures involve numerical algorithms for predicting damage in ship grounding and collision, accident scenarios and innovative design concepts to prevent oil spills and minimize structural damage. The grounding models cited in this study are the DAMAGE program, developed at MIT and the method of Wang which involves four failure modes. Furthermore, the collision models cited are the SIMCOL model, developed at Virginia Tech, the DAMAGE model, the ALPS/SCOL and the DTU model, developed in the technical university of Denmark.

Xia (2001) elaborated a significant survey about bow structure crushing in a ship collision event including the numerical analysis of bow collision in different situations including the collision of a bow structure against a rigid wall, a stationary and a moving double hull tanker. The analysis of the results is focused in obtaining the force penetration curves of the collision in all the cases in different longitudinal positions of the struck ship unless there was not presented an experimental validation. This work also appended a step-by-step guide to generate the model geometry using Autocad, FastShip and SafeHull softwares.

Kitamura O. (2000) developed a FE analysis to evaluate the improvement on the energy absorption capability when introduce a buffer system in a bulbous bow, Fig. 7. Design alterations to the form and stiffening of a bulbous bow were analyzed. The ultimate strength and absorbed energy of the bow and lateral hull structures are discussed based on the simulation results. Later, Kitamura (2002) simulates a ship collision event using a FE model which contains about 720 thousands elements. The developed simulations point out several uncertain factors involved in simplified analytical approaches. Some unusual aspects of a ship collision event are analyzed, aspects such as coupling with hull girder horizontal bending, equivalent failure strain, deformation of supporting structure, forward velocity of struck ship, collision angle, bending of bow, folding of flat plates, folding of stiffened panels and partial crushing of bow structure. This study concluded about the importance of all these aspects in a numerical simulation of a ship collision event to get good agreement with real data.



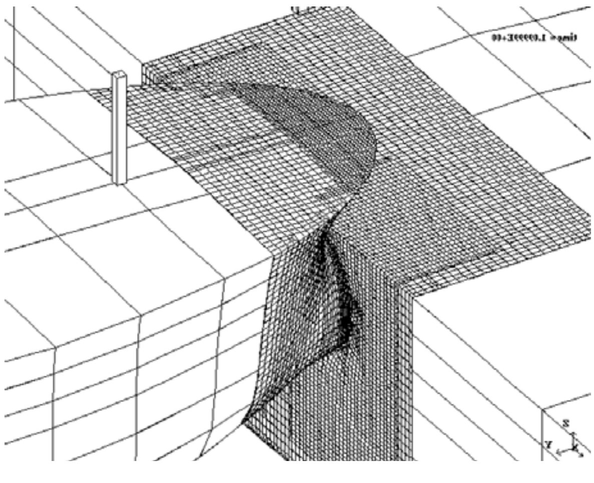


Figure 7. Ship collision of a standard sharp bulbous bow against a side hull, Kitamura (2000).

Wisniewski and Kolakowski (2003) simulated a collision of a double hull crude oil carrier ship and a container vessel with a bulbous bow using the FEM. This model includes crushing and tearing of the material and evaluates the effect of the implemented material model, friction coefficient, striking ship velocity, motion of the stuck ship and mass scaling. To validate these models, the authors simulated the indentation of a stiffened structure by a rigid cone and compared with an experimental reference test.

Ozguc *et al.* (2005) investigate the collision resistance and residual strength of a ship using the FEM. This research analyzed the collision of two geometries of rigid bulbous bows against two lateral hulls, structures with single and double skins. The resistance forces, energy absorption and penetration depth were evaluated for various collision scenarios. This analysis was validated by modeling an experimental test of a naval structure developed by other authors.

A brief state-of-art of methods to evaluate the residual strength was surveyed but only the Smith's method together to the average stress-strain relationships were used to evaluate it. In addition, the corrosion effect was introduced in the evaluation by reducing the structure thickness.

To develop the basis of the fluid-structure interaction study, Zhang (2007) initially model a bidimensional sloshing experiment in which a rectangular tank with a baffle at the center of the bottom and filled at 60% with a fluid is excited with a horizontal harmonic motion. The experimental response, related to the reaction force at the lateral of the tank, is compared with numerical model in which the fluid is modeled as solid elements, based in the arbitrary langrangian eurelian FEM with a contact algorithm; both techniques allow to create a new undistorted mesh for fluid domain and the calculation to continue. This analysis was the foundation to develop huge numerical simulations of the ship collisions: the first only considering the middle cargo tank of the struck ship filled, the second only considering the external fluid surrounding the striking and struck ships and the final model including both influences, Fig. 8.

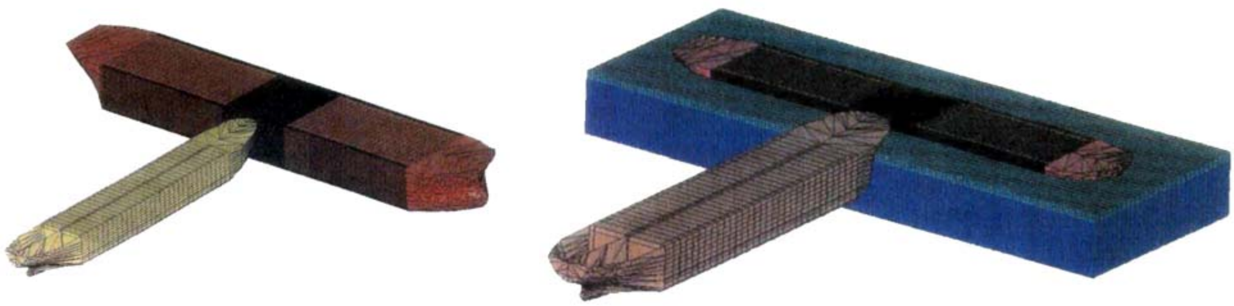


Figure 8. Modeling of a ship collision including only the internal and both internal and external fluid-structure interaction, Zhang (2007).

Yagi *et al.* (2008) compare the buffer bow characteristics during a ship collision event of a sharp entrance angle bow and a conventional bulbous bow using a FE analysis. A collision scenario where the striking ship hits the side hull of a tanker ship perpendicularly was modeled. The results demonstrated that the buffer characteristics of sharp bow are higher than the conventional bulbous bow, since much more energy is dissipated for the same penetration.

5. SCALED SHIP COLLISION EXPERIMENTS

Scaled models are important in naval engineering since the ship size makes too expensive to test actual prototypes. Hydrodynamic ship aspects are traditionally evaluated by scaled models but the structural behavior of the ship during a ship collision event is not a common study in the ship research community. Hence, Blok and Dekker (1979) tested a scaled ship model being displaced laterally to collide against a static protected jetty to measure the added mass due to the hydrodynamic effect. The tanker model corresponds to a 225,000 dwt at a scale of 1:75.

Hagiwara *et al.* (1983) analyzed experimentally the ship collision event by constructing small scaled models made of thin steel plates (1:10 scale), so to overcome the complexity of developing a theoretical analysis, Fig. 9. The aim was to estimate the energy involved in low-energy ship collision events but the experiments failed since some aspects such as the non-similarity in material failure and the omission of some structural member to simplify a scaled construction influenced strongly the results.

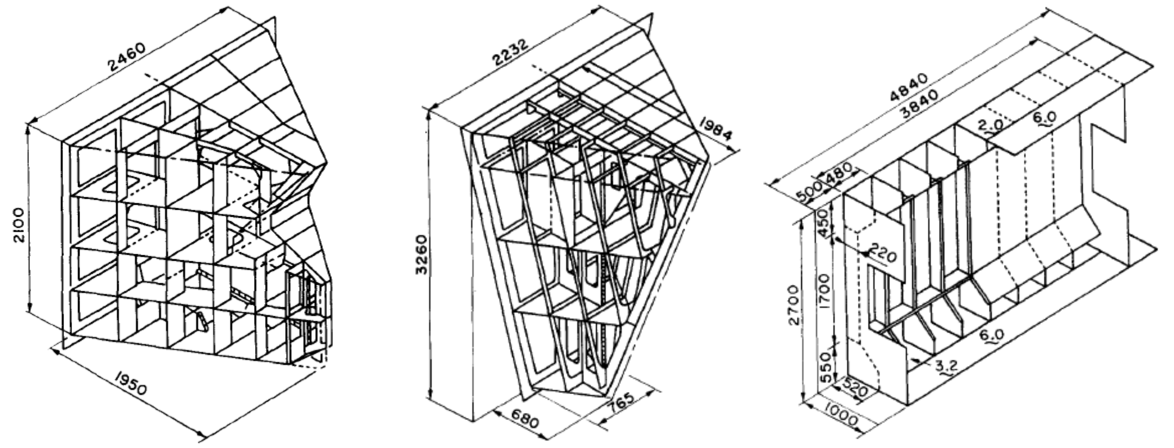


Figure 9. Dimensions of scaled experimental model of bulbous bow and side structure, Hagiwara *et al.* (1983).

In order to obtain detailed actual data from a ship collision event, four full scale ship collision experiments were carried as a joint project of Dutch-Japanese governmental organizations. Vredeveldt and Wevers (1992) and Carlebur (1995) reported the results of these tests, Fig. 10a. The ships are inland waterway tankers of 80 m in length. The contact forces, impact duration, ships motion, bow penetration and strain in the lateral hull of the struck ship were measured. Moreover, the deformation energy and damaged volume were also evaluated. The main motions observed in the struck ship, during the collision, were found significant in the sway and yaw directions but the roll motion was insignificant. Only the third part of the total kinetic energy was dissipated in deformation. Ohtsubo *et al.* (1994) examined the failure of tanker structures of these full-scale experiments. The bow of the striking ship was reinforced to collide four times and two tanks of the struck ship were modified, one to double hull and the other to double hull with stringer decks. Structural failure required to be investigated experimentally in a large-scaled model since the induced failures are similar to actual ship failures and difficult to obtain by using small-scale models. Also, the tests showed that dynamic effects such as inertia forces and strain rate sensitivity were negligible.

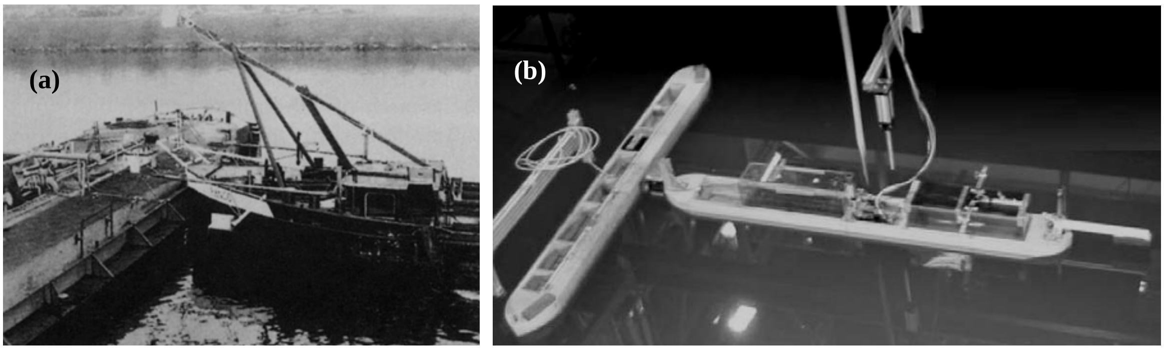


Figure 10. (a) Large-scale collision test, Vredeveldt and Wevers (1992) and (b) Scaled-model, Tabri *et al.* (2008).

Lehmann and Peschmann (2002) developed a large-scale ship collision experiment in a 1:3 scale by adapting two inland waterway vessels. A bulbous bow collide the lateral hull of the struck ship at 2.55 m/s, both structures suspended by tie rods. The dimensions were based in a medium sized double–hull tanker of 30,000 dwt. Three FE models were developed considering diverse hull materials: normal steel, austenitic inner shell and austenitic inner and outer shells. The comparison of the results demonstrated that the austenitic steel absorbs more energy than common steel.

Tabri *et al.* (2008) built scaled ship models to simulate a ship collision event. The tanker models made of wood were constructed following a scale of 1:35, Fig 10b. The ship collision was considered perpendicular, a rigid bulbous bow instrumented with a force sensor was mounted in front of the striking ship and the side of the struck ship made with polyurethane foam to imitate the deformation behavior of the struck structure. The results demonstrated that the mass ratio is the most influent parameter in determining the energy absorbed during the collision, even more than collision velocity or structural response.

7. ACKNOWLEDGEMENTS

The authors would like to thank the Brasilian research funding agency FINEP for the financial support.

8. REFERENCES

Akita, Y., 1972, “Studies of collision-protective structures in nuclear power ships”. Nuclear Eng. and Design, Vol. 19, pp. 365-401.

Alsos, H.S. and Amdahl, J., 2009, “On the resistance to penetration of stiffened plates, Part I – Experiments”. International Journal of Impact Engineering, Vol. 36, No. 6, pp. 799-807.

Alsos, H.S., Amdahl, J. and Hopperstad, O.S., 2009, “On the resistance to penetration of stiffened plates, Part II – Numerical analysis”. International Journal of Impact Engineering, Vol. 36, No. 7, pp. 875-887.

Amdahl, J. and Stornes, A., 2001, “Energy dissipation in aluminium, high-speed vessels during grounding and collision”. Proceedings of the 2nd international conference on collision and grounding of ships, Denmark.

Ammerman, D.J. and Daidola, J.C., 1996, “A comparison of methods for evaluating structure during ship collisions”. Int. Conf. on Designs and Methodologies for Collision and Grounding Protection of Ships, USA, pp. 21-23.

Awal, Z.I. and Islam, M.R., 2008, “A study on ship capsizing due to collision”. Jurnal Mekanikal, No. 26, pp. 22-36.

Bai, Y., Bendiksen, E. and Pedersen, P.T., 1993, “Collapse analysis of ship hulls”. Mar. Structures, Vol. 6, pp. 485-507.

Blok, J.J. and Dekker, J.N., 1979, “On hydrodynamic aspects of ship collision with rigid or non-rigid structures”. Offshore Technology Conference, USA.

Blok, J.J., Brozius, L.H. and Dekker, J.N., 1983, "The Impact Loads of Ships Colliding With Fixed Structures". Offshore Technology Conference, USA.

Brown, A.J., 2002, "Modeling structural damage in ship collisions". Ship Structure Committee.

Brown, A. and Chen, D., 2002, "Probabilistic method for predicting ship collision damage". Oceanic Engineering International, Vol. 6, No. 1, pp. 54-65.

Brown, A. and Sajdak, J., 2004, "Predicting probabilistic collision damage extents for tanker oil outflow assessment and regulation". Transactions of the SNAME A, Vol. 112, pp. 514-522.

Brown, A., Moon, W. and Louie, J., 2002, "Structural Design for Crashworthiness in Ship Collisions". SNAME Transactions, Vol. 110, pp. 499-512.

Brown, A.J., Tikka, K., Daidola, J., Lutzen, M. and Choe, I., 2000, "Structural Design and Response in Collision and Grounding", SNAME Transactions, Vol. 108, pp. 447-473.

Calebur, A.F.C., 1995, "Full-scale collision tests". Safety Science, Vol. 19, pp. 171-178.

Caridis, P.A., Samuelides, E. and Frieze, P.A., 1994, "On the dynamic response of ship plating under lateral impact". International Journal of Impact Engineering, Vol. 15, No. 2, pp. 149-164.

Chen, D., 2000, "Simplified ship collision model". Dissertation of Master in Ocean Engineering, Virginia Tech.

Egge, E.D. and Böckenhauer, M., 1991, "Calculation of the collision resistance of ships and its assessment for classification purposes". Marine Structures, Vol. 4, pp. 35-56.

Endo, H., Yamada, Y., Kitamura, O. and Suzuki, K., 2002, "Model test on the collapse strength of the buffer bow structures". Marine Structures, Vol. 15, pp. 365–381.

Hagiwara, K., Takanabe, H. and Kawano, H., 1983, "A proposed method of predicting ship collision damage". International Journal of Impact Engineering, Vol. 1, No. 3, pp. 257-279.

Hayduk, R.J. and Wierzbicki, T., 1984, "Extensional collapse modes of structural members". Computers & Structures, Vol. 18, No. 3, pp. 447-458.

Hong, L. and Amdahl, J., 2007, "Plastic design of laterally patch loaded plates for ships". Mar. Structures, Vol. 20, pp. 124-142.

Hong, L. and Amdahl, J., 2008, "Crushing resistance of web girders in ship collision and grounding". Mar. Structures, Vol. 21, pp. 374-401.

Hutchison, B. L., 1986, "Barge collisions, rammings and groundings - an engineering assessment of the potential for damage to radioactive material transport casks", Report No SAND85-7165 TTC-05212.

Jones, N., 1979, "A literature survey on the collision and grounding protection of ships". Ship Structure Committee.

Kim, H-S. and Wierzbicki, T., 2001, "Crush behavior of thin-walled prismatic columns under combined bending and compression". Computer and Structures, Vol. 79, pp. 1417-1432.

Kitamura, O., 2000, "Buffer Bow Design for the Improved Safety of Ships". Ship Structure Committee Symposium, USA, No. 17.

Kitamura, O., 2002, "FEM approach to the simulation of collision and grounding damage". Marine Structures, Vol. 15, pp. 403-428.

Lehmann, E. and Peschmann, J., 2002, "Energy absorption by the steel structure of ships in the event of collisions". Marine Structures, Vol. 15, pp. 429-441.

Lenselink, H. and Thung, K.G., 1992, "Numerical simulations of the Dutch-Japanese full scale ship collision tests", Conference on Prediction Methodology of Tanker Structural Failure, Japan.

Lützen, M., 2001, "Ship collision damage". Ph.D. Thesis, Department of Mechanical Engineering, Technical University of Denmark, Lyngby.

Manolakos, D.E. and Mamalis, A. G., 1985, "On ship collisions: the plastic collapse of longitudinally framed shell plating subjected to oblique loading". International Journal of Impact Engineering, Vol. 3, No. 1, pp. 41-55.

Mazzariol, L.M., Calle, M.A.G., Oshiro, R.E. and Alves, M., 2010, "Scaling of stiffened panels subjected to impact loading". Iberian-latin-american congress on computational methods in engineering. Mecánica Computacional. Vol. XXIX. pp. 1275-1289.

McDermott, J.F., Kline, R.G., Jones, Jr. E.L., Maniar, N.M. and Chiang, W.P., 1974, "Tanker Structural Analysis for Minor Collisions", SNAME Transactions, Vol. 82, pp. 382-414.

Minorsky, V.V., 1959, "An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants". Journal of Ship Research, Vol. 3, No. 1.

Mohammed, A.K., Amdahl, J. and Skallerud, B., 2001, "Collapse analysis of stiffened panels during accidental conditions". Proceedings of Offshore Mechanics and Arctic Engineering, Brazil.

Motora, S., 1966, "On the measurement of added mass and moment of inertia of ship in steering motion". Maneuvering symposium, Washington, USA.

Ohtsubo, H., Kawamoto, Y. and Kuroiwa, T., 1994, "Experimental and numerical research on ship collision and grounding of oil tankers". Nuclear Engineering and Design, Vol. 150, pp. 385-396.

Oshiro, R.E. and Alves, M., 2009, "Scaling of structures subject to impact loads using a power law constitutive equation". International Journal of Solids and Structures, Vol. 46. pp. 3412-3421.

Ozguc, O., Das, P.K. and Barltrop, N., 2005, "A comparative study on the structural integrity of single and double side skin bulk carriers under collision damage". Marine Structures, Vol. 18, pp. 511-547.

Paik, J.K., Choe, I.H., Thayamballi, A.K., Pedersen, P.T. and Wang, G., 1999, "On rational design of double hull tanker structures against collision", SNAME Annual meeting.

Paik, J.K. and Pedersen, P.T., 1996, "Modelling of the internal mechanics in ship collisions". Ocean Engineering, Vol. 23, No. 2, pp. 107-142.

Parks, M.B. and Ammerman, D.J., 1995, "An assessment of simplified methods to determine damage from ship-to-ship collisions". Int. conference on packaging and transportation of radioactive materials, USA.

Petersen, M.J., 1982, "Dynamics of Ship Collisions", Ocean Engineering, Vol. 9, No. 4, pp. 295-329.

Pedersen P.T., Simonsen, B.C. and Lutzen M., 2000, "Rapid Prediction of Damage to Struck and Striking Vessels in a Collision Event". Ship Structures for the New Millennium, USA.

Pedersen, P.T. and Li, Y., 2009, "On the global ship hull bending energy in ship collisions". Marine Structures, Vol. 22, pp. 2-11.

Pedersen, P.T. and Zhang, S., 1998, "On impact mechanics in ship collisions". Marine Structures, Vol. 11, pp. 429-449.

Pedersen, P.T. and Zhang, S., 1999, "Collision analysis for Ms Dextra". Safer Euroro Spring meeting, p. 31, France.

Pedersen, P.T. and Zhang, S., 2000, "Effect of ship structure and size on grounding and collision damage distributions". Ocean Engineering, Vol. 27, pp. 1161-1179.

Porter, V.L. and Ammerman, D.J., 1995, "Analysis of a ship-to-ship collision". Int. conference on packaging and transportation of radioactive materials, USA.

Qi, E., Cui, W. and Wan, Z., 2005, "Comparative study of ultimate hull girder strength of large double hull tankers". Marine Structures, Vol. 18, pp. 227-249.

Reardon, P.C. and Sprung, J., 1996, "Validation of Minorsky's ship collision model and use of the model to estimate the probability of damaging a radioactive material transportation cask during a ship collision", Int. conference on design and methodologies for collision and grounding protection of ships, USA.

Reckling, K.A., 1981, "Overall Structural Response of a Ship Struck in a Collision". Extreme Load Response Symposium, pp. 115-124, USA.

Reckling, K.A., 1983, "Mechanics of minor ship collisions". Int. J. of Impact Engineering, Vol. l, No. 3, pp. 281-299.

Rosenblatt & Son, Inc, 1975, "Tanker Structural Analysis for Minor Collision", USCG Report, CG-D-72-76.

Samuelides, E., 1984, "Structural dynamic and rigid body response coupling in ship collisions". Ph.D. Thesis, Glasgow University, United Kingdom.

Samuelides, E. and Frieze, P.A., 1989, "Fluid-Structure Interaction in Ship Collisions". Marine Structures, Vol. 2, pp. 65-88.

Servis, D.P. and Samuelides, M., 1999, "Ship Collision Analysis Using Finite Elements". Internal Report, National Technical University of Athens.

Simonsen, B.C., 1999, "Theory and Validation for the DAMAGE Collision Module". Joint MIT Industry Program on Tanker Safety, Report No. 67.

Simonsen, B.C. and Ocakli H., 1999, "Experiments and theory on deck and girder crushing". Thin-Walled Structures, Vol. 34, pp. 195-216.

Simonsen, B.C. and Törnqvist, R., 2004, "Experimental and numerical modelling of ductile crack propagation in large-scale shell structures". Marine Structures, Vol. 17, pp. 1-27.

Skallerud, B. and Amdahl, J., 1998, "Modelling methodologies with beam finite elements for collapse analysis of tubular members/cylindrical shells". Int. Conference Thin-walled structures, Singapore, pp. 629-639.

Soares, C.G., Basu, R., Simonsen, B.C., Egorov, G.V., Hung, C.F., Lindstrom, P., Samuelides, E., Vredeveldt, A.W. and Yoshikawa, T., 2009, "Damage assessment after accidental events", Int. Ship and Offshore Structure Congress.

Suzuki, K., Ohtsubo, H. and Sajit, C., 2000, "Evaluation Method of Absorbed Energy in Collision of Ships with Anti-Collision Structure". Ship Structure Committee Symposium, USA, No. 12.

Tabri, K., Määttänen, J. and Ranta, J., 2008, "Model-scale experiments of symmetric ship collisions". Journal of Marine Science and Technology, Vol. 13, pp. 71-84.

Tabri, K., Broekhuijsen, J., Matusiak, J. and Varsta, P., 2009, "Analytical modelling of ship collision based on full-scale experiments". Marine Structures, Vol. 22, pp. 42-61.

Tabri, K., Varsta, P. and Matusiak, J., 2009, "Sloshing interaction in ship collisions - An experimental and numerical study". Ocean Engineering, Vol. 36, pp. 1366-1376.

Tabri, K., Varsta, P. and Matusiak, J., 2009, "Numerical and experimental motion simulations of nonsymmetric ship collisions". Journal of Marine Science and Technology, Vol. 15, No. 1, pp. 87-101.

Vakkalanka, S., 2001, "Simplified bow model for a striking ship in collision". Dissertation of Master in Ocean Engineering, Virginia Tech.

Van Mater, Jr.P.R., Giannotti, J., Jones, N. and Genalis, P., 1979, "Critical evaluation of low-energy ship collision damage theories and design methodologies". Ship Structure Committee.

Vaughan, H., 1978, "Bending and tearing of plate with application to ship-bottom damage". Naval Architects, Vol. 3. pp. 97-99.

Vredeveldt, A.W. and Wevers, L.J., 1992, "Full scale ship collision tests". First Joint Conference on marine Safety and Environment/Ship production, Netherlands.
Wang, G., Arita, K. and Liu, D., 2000, "Behavior of a double hull in a variety of stranding or collision scenarios". Marine Structures, Vol. 13, pp. 147-187.
Wang, G., Ji, C., Kujala, P., Lee, S-G., Marino, A., Sirkar, J., Suzuki, K., Pedersen, P.T., Vredeveldt, A.W. and Yuriy, V., 2006, "Collision and grounding". Int. Ship and Offshore Structures Congress, United Kingdom.
Wierzbicki, T., 1983, "Crushing Behavior of Plate Intersections", Structural Crashworthiness, Chapter 3, Butterworth and Co., London.
Wierzbicki, T., 1995, "Concertina tearing of metal plates". Int. J. of Solids Structures, Vol. 32, No. 19, pp. 2923-2943.
Wierzbicki, T. and Suh, M.S., 1988, "Indentations of tubes under combined loading". International Journal of Mechanical Science, Vol. 30, No. 3-4, pp. 229-248.
Wierzbicki, T. and Huang, J., 1991, "Initiation of plastic folding mechanism in crushed box columns". Thin-Walled Structures, Vol. 13, pp. 115-143.
Wierzbicki, T. and Driscoll, J.C., 1995, "Crushing damage of web girder under localized static loads". Journal of constructional steel research, Vol. 33, pp. 199-235.
Wisniewski, K. and Kolakowski, P., 2003, "The effect of selected parameters on ship collision results by dynamic FE simulations". Finite Elements in Analysis and Design, Vol. 39, pp. 985-1006.
Woisin, G., 1979, "Design against collision". Schiff & Hafen, Vol. 31, No. 2, pp. 1059-1069.
Wu, F., Spong, R. and Wang, G., 2004, "Using numerical simulation to analyze ship collision". Int. Congress on Collision and Grounding of Ships, Japan.
Xia, J., 2001, "Finite element analysis of ship collision". Dissertation of Master in Ocean Engineering, Virginia Tech.
Yagi, S., Kumamoto, H., Muragishi, O., Takaoka, Y. and Shimoda, T., 2009, "A study on collision buffer characteristic of sharp entrance angle bow structure". Marine Structures, Vol. 22, No. 1, pp. 12-23.
Yamada, Y., 2006, "Bulbous buffer bows: A measure to reduce oil spill in tanker collisions". Ph.D. Thesis, Department of Mechanical Engineering, Technical University of Denmark.
Yamada, Y and Endo, H., 2008, "Experimental and numerical study on the collapse strength of the bulbous bow structure in oblique collision". Marine Technology, Vol. 45, No. 1, pp. 42-53.
Yamada, Y., Endo, H., Kawano, H. and Hirakata, M., 2003, "Collapse Mechanism of the Buffer Bow Structure on Axial Crushing". Int. Offshore and Polar Engineering Conference, USA.
Yamada, Y. and Pedersen, P., 2008, "A benchmark study of procedures for analysis of axial crushing of bulbous bows". Marine Structures, Vol. 21, pp. 257-293.
Yang, P.D.C. and Caldwell, J.B., 1988, "Collision energy absorption of ships' bow Structures". International Journal of Impact Engineering, Vol. 7, No. 2, pp. 181-196.
Zhang, S., 1999, "The Mechanics of Ship Collisions", Ph.D. Thesis, Department of Naval Architecture and Offshore Engineering, Technical University of Denmark.
Zhang, A., 2007, "A study on ship collision and grounding using nonlinear finite element method". Thesis of PhD, University of Tokyo.
Zhang, A. and Suzuki, K., 2007, "A study on the effect of stiffeners on quasi-static crushing of stiffened square tube with non-linear finite element method". International Journal of Impact Engineering, Vol. 34, pp. 544-555.
Zhang, A. and Suzuki, K., 2007, "A comparative study of numerical simulations for fluid–structure interaction of liquid-filled tank during ship collision". Ocean Engineering, Vol. 34, pp. 645-652.
Zhu, L. and Faulkner, D., 1994, "Dynamic inelastic behavior of plates in minor ship collisions". Journal of Impact Engineering, Vol. 15, pp. 165-178.
Zhu, L. and Faulkner, D., 1996, "Damage estimate for plating of ships and platforms under repeated impacts". Marine Structures, Vol. 9, pp. 697-720.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.