Predicting Ship Structure Performance in Accidents

Ge Wang  
American Bureau of Shipping, Houston

A.K. Seah  
American Bureau of Shipping, Singapore

Yung Shin  
American Bureau of Shipping, Houston

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Abstract

With increasing demand for safety of life at sea and protection of the environment, there has been considerable interest to predict the damages an accident will cause to the ship so that the consequences in terms of human life, property loss and marine pollution can be appropriately accounted for at the design stage.

Standards for design against accidents should be developed and should include definition of accident scenarios, procedures for evaluating consequences and criteria for approval or acceptance of a design. One of the key issues for such a standard is the tool used to estimate the damage extents of a ship in accidents.

Simulation tools and full scale model tests are commonly used in passenger car designs to mitigate consequences of road accidents. Similar tools for obvious reasons cannot be used on a regular basis for ship design. However they have been used in a limited scale for research purposes. More recently emerging simplified analytical methods become available. These methods are based on simplified characteristics of damage process and employ theoretical formulae to predict behaviors of structural components.

As a result of extensive studies, many damage characteristics of ship structures have been identified and solved using simple expressions. These methods and more newly developed methods have been successfully applied to a variety of accident scenarios, including ship-ship collision, ship-platform collision, ship-bridge collision, grounding, stranding. These methods are discussed in this paper.
INTRODUCTION

It is well known that ship structures are inherently redundant. Experience has shown that in the event of an accident, such as collision or grounding, they, more often than not, had sufficient residual strengths to prevent themselves from falling apart. Maritime regulations, likewise, rather than specifying reserve strengths, have concerned themselves with mandating reserve stability so that in the event of damage, ships will not founder. In respects of protecting the marine environment from polluting substances carried by ships, regulatory requirements also mandate the erection of inner hulls located at specified distances from the side shell and bottom, so that in the event of collision or grounding accidents, the inner hulls will prevent the outflow of hazardous cargoes. More recently, the integrity of the ship structure in general and that of inner hull in particular in the event of an accident have been called into question in many quarters.

In subscribing to the safety philosophy of, on the one hand, preventing accidents, and on the other, mitigating the consequences should accidents occur, it is necessary to assure that the functions of the imitating measures are preserved in the event of an accident. In this respect, there has been considerable interest in recent years to predict the damages a collision or grounding accident would cause to ships so that the mitigating measures for such accidents could be appropriately accounted for at the design stage.

A broad spectrum of issues related to collisions and grounding has been investigated. The advances in technology enhance the understanding of this complex problem. Research has been yielding results of practical importance in many areas.

This paper introduces the various approaches that have evolved in recent years. A general framework is presented with a view to shed light on how this can contribute to developing ship structure design standards. Focus is placed on predicting the performance of ship structures in collision or grounding accidents. While much research is still on-going to develop and refine these prediction methodologies, for simplicity this paper divide them into two categories: the simplified analytical methods and the non-linear FEM simulations. These two approaches are described and compared. Implications to designs are also presented.

DESIGN AGAINST COLLISION AND GROUNDING ACCIDENTS

A collision or grounding accident can lead to potentially costly consequences of loss of lives and damage to property or the environment, or both. As past accidents have demonstrated the indirect cost of compensation and bad publicity can be a great deal higher. This has been the driving force in recent years for developing standards for design against collision and grounding accidents.

A standard for design against such accidents must include:

- definition of accident scenarios,
- procedures for evaluating the risks and,
- criteria for acceptance of a design.

Whether a design is acceptable or not may be judged by determining the risks of the design for a set of accident scenarios and evaluating if such risks falls within an acceptable limit using the specified (or recommended) evaluation procedures.

In determining the risks, one must take into consideration the consequence and the probability of occurrence for each scenario. Hence, scenarios with high consequence but low likelihood of occurrence, may require as careful an evaluation as scenarios that are likely to happen but have moderate or small consequences.

There are a variety of tools for assessing different aspects of an accident. Some predict the probabilities of occurrence of accidents; some calculate the structural response in an accident; some deal with hypothetical oil outflow following an accident; some analyze the residual strength of
a damaged hull; some evaluate the stability following a loss of watertight integrity; and some assess the environmental impact.

An important aspect of the assessment is the tool used to evaluate the extent of damage to a ship in the event of a collision or grounding. Such evaluation tools are normally based on the physics or the mechanics of solid bodies in motion and can vary from simple formulae or simplified analytical methods to, in some cases, powerful simulation techniques. The main challenges are in predicting the energy released for dissipation in the colliding structures and the strength or resistance of the structures in absorbing the impact. The last decade saw remarkable advances in these two topics. For consistency in evaluation, the design standard must specify a common set of tools for all accident scenarios under investigation.

Acceptance criteria for a design may be deterministic, probabilistic or semi-probabilistic. Some of the deterministic criteria used in regulations today include damage extent in terms of minimum distance of inner hull from outer skin, hypothetical oil outflow, residual strength of the damaged ship, and reserve stability. Environmental damage however has not yet been used nor have effects of variations in ship structural design on final damage extent.

SIMPLIFIED ANALYTICAL METHODS

For purposes of evaluating collision or grounding, a designer needs to have information on the momentum of the colliding bodies and the global energy absorption capacities of these bodies in the form of detailed behavior of each individual structural component that made up these bodies. For analysis, it is necessary to develop on the one hand, an estimate of the energy to be dissipated and on the other, a set of simplified theoretical formulae capturing the characteristics of the damage process in the structure. These are discussed further hereunder.

Analysis procedure

A simplified analytical approach may be presented using Fig. 1, which shows the typical steps for analysing ship-ship collisions.

The entire analyses can be split into the external and internal collision mechanics. The former involves simulation of the time dependent rigid body motion of the two colliding vessels with account of collision forces and the added mass effect of the surrounding water.

The latter (i.e., the internal collision mechanics) evaluates the structural responses of the two bodies during the collision. The interest here is in assuming that the kinetic energy of the colliding bodies is converted at least in large part to strain energy of the deforming structures. Usually force-indentation response curves are plotted for both bodies and by integrating the area below the curves, the strain energy for the two structures are estimated.

Considering the principle of energy conservation, and neglecting frictional and other losses, the total loss in kinetic energy at the end of the collision should equal the total strain energy dissipated by the structural deformation of both the collided and the colliding vessel structures. Hence in a ship to ship collision,

\[ \Delta E = W = W_s + W_a \]  

where \( \Delta E \) = total loss in the kinetic energy, \( W \) = total strain energy dissipated by structural damage of both the collided and the colliding vessels, \( W_s \), \( W_a \) = strain energy component dissipated by damage of the side structure of the collided vessel or the bow structure of the colliding vessel, respectively.
External mechanics - estimate of kinetic energy

The external mechanics deals with the physical motions of ships involved in an accident. By means of equations of motion or by an integrated approach and considering conservation of energy, momentum and angular momentum during the impact, analytical expressions for the energy to be dissipated can be derived (Pedersen and Zhang 1998, Paik et al. 1999, Suzuki et al. 2000).

A simplest ship-ship collision scenario is that ship one with an initial speed of \( V_r \) strikes perpendicularly with a ship of speed zero. At the end of the collision, the common velocity of the two ships is \( V \) in the direction perpendicular to the sailing direction of the struck ship. The collision angle between the two vessels is assumed to be kept constant during the collision, i.e., the collided ship is assumed not to rotate during the collision. According to the momentum equilibrium in the direction normal to the collided vessel in a free floating situation, the common speed at the end of the collision can be predicted:

\[
V = \frac{(1 + C_{a1})m_1 \cdot V_r}{(1 + C_{a1})m_1 + (1 + C_{a2})m_2}
\]  

(2)

where \( C_{a1} \) and \( C_{a2} \) are the added mass coefficients for the colliding and collided ships respectively, representing the effect of the surrounding water during the collision, and \( V_r \) is the relative velocity between the two vessels. The added mass coefficients have been taken as \( C_{a1} = 0.03 \sim 0.1 \) and \( C_{a2} = 0.4 \sim 0.8 \).

The total loss of kinetic energy during the collision of the two vessels in a free floating condition is then given by

\[
\Delta E = \frac{1}{2} \left(1 + C_{a1}\right)m_1 \left(V_r\right)^2 - \frac{1}{2} \left(1 + C_{a1}\right)m_1 + \left(1 + C_{a2}\right)m_2 \left(V_r\right)^2
\]

\[
= \frac{1}{2} \left(1 + C_{a1}\right) \left(1 + C_{a2}\right) m_1 m_2 \left(V_r\right)^2
\]  

(3)

Thus once the ship masses, relative impact speed and colliding angle are known, the loss of kinetic energy can be estimated from Eq. (3).
Equation (3) tells us that in a collision the kinetic energy loss is proportional to the square of the collision speed. In the case of tankers, to prevent oil spillage in a collision, it is obvious and of crucial importance that the speed of the ships be maintained low.

**Internal mechanics - structural behavior**

Internal mechanics evaluates the energy absorption of structures in an accident, including complex structural responses of deep collapse, large plastic deformation, fracture and friction. It is normally assumed that the strain energy is negligibly small for deformation outside the contact region and the contact area is local and small.

A ship’s hull is a complex structural system consisting of plating attached through welding to stiffeners supported by frames, web girders and bulkheads. However, for simplicity two typical structural behaviors are considered dominant and have been studied in greater details. These are

- the “local” behaviors of plates under large impact loads and of plate tearing, and
- the “global” behavior of progressive structural damage modeling.

**Plate under large impact load**

In classical structural mechanics, there are two basic load types: concentrated loads and distributed loads. Loads on a structure are generally modeled as either or a combination of both. These classical load models are not always appropriate for collision studies; a striking object may not be sharp enough to be idealized as a point load, nor big enough so that it can be viewed as loads distributed over a certain area.

In order to more accurately address this need, refined plate-punching model has been developed. This new model has one additional parameter for object geometry, i.e., the radius of the sphere (Fig. 2). Laboratory tests have demonstrated that a structure shows much higher resistance when the striker is blunt (large radius) than when it is sharp (small radius). Newly developed theoretical formulae (Wang 2002) capture this phenomenon, which is not predictable using classical structural mechanics theory.

**Ruptured plate**

The behavior of a plate after material rupture occurs due to punching is illustrated taking Test P-50 of Wang et al. (2000) as an example. As the punching object (a spherical nose) strikes, the following damage sequence is observed:

- circumferential necking in the plate
- plate cracking, however cracks did not propagate all the way round to detach a "cap" of material
- "cap" was left hinged to one side as the penetration proceeded
- radial necking
- some radial cracks
- fractures along the necked regions
- strips between cracks bent into curls, or petals
- petals pushed sideways and bent to a larger extent.
- cracks advanced as the penetration proceeded.
A ruptured plate has three mechanisms: very large stretching in the vicinity of the crack tips, prominent bending of plate "flaps" or petals remote from the striker, and friction between the flaps and the striker. The local stretching separates the material, which then has to bend along hinge lines connecting the crack tips. These three mechanisms interact with each other and as a result, the plate holds the load.

The contribution from membrane stretching, plastic bending and friction are summed up following Eq. (4). A closed form expression can then be derived for the behavior of a ruptured plate with some cracks (Wang et al. 2000):

$$ F = 1.51\sigma_0 t^{1.5} n^{0.5} \sin^{0.5} \left( \frac{(n-2)\pi}{2n} \right) \left( \tan \theta + \mu \right), \quad (4) $$

where, $F$ is the load, $\sigma_0$ is the flow stress, $t$ is the plate thickness, $l$ is the tearing length, $2\theta$ is the spreading or apex angle of the cone, $\mu$ is the friction coefficient, and $n$ is the number of cracks.

Optimizing Eq. (4) with respect to $n$ leads to the observation that $F$ becomes the smallest when $n$ is the smallest. In other words, the fewer the cracks, the lower the load will become. In many tests on steel plates published to date, three or four cracks were commonly reported. Fig. 3 shows that four cracks in the radical direction results after the plate is ruptured due to the penetration of a rigid sphere.
cone. This observation is in line with the conclusion of Eq. (4): structures tend to a condition of minimum energy. This is also evidence supporting the conclusion that the cracking mechanism interacts with the other mechanisms of stretching and bending to achieve low energy.

Plate tearing

Plate tearing is regarded as highly relevant to a bottom raking process, where a ship’s bottom is torn open sometimes for as long as tens or even hundreds of meters in length. Similarly for the deck in a collision, which is cut and torn by the striking bow. Plate tearing (or cutting by some) has been extensively investigated recently.

The plate tearing refers to a plate cut by a rigid wedge (Fig. 4). As the wedge pushes into the plate persistently, the following behavior is observed:

- the plate buckles and bends out of plane
- upon reaching the plate’s ultimate strength but before separation of material, load declines
- as the wedge pushes on further, plate separates and the load picks up again – commencement of tearing
- plate is torn apart in front of the wedge tip in the transverse direction. Near the wedge tip, the plate develops a global deformation pattern, where the plate deforms out of the plane and separates at or close to the proximity of the wedge tip
- separated plate bends over, forming two curls or flaps
- curved plate flaps and rolls up in the wake of the
- load keeps building up as the tearing curls reverse.

Wierzbicki and Thomas (1993) developed a kinematic model describing the entire field of the deformation, including the far-field of two flaps and the near-tip field of local stretching. Fracture is assumed to explain the material separation. The local stress state near the wedge tip is described using a fracture mechanics parameter of crack tip opening displacement (CTOD). The work required to propagate the crack is expressed as a function of the CTOD parameter. The analytical formula has the following expression:

\[
F = 1.67 \sigma_0 (\delta_0)^{0.2} t^{1.6} \theta^{0.4} \frac{1}{(\cos \theta)^{0.8}} \left[ (\tan \theta)^{0.4} + \frac{\mu}{(\tan \theta)^{0.8}} \right]
\]  

(5)

where, \( F \) is the load, \( \sigma_0 \) is the flow stress, \( t \) is the plate thickness, \( l \) is the tearing length, \( \delta_0 \) is a crack opening displacement parameter (CTOD), \( 2\theta \) is the spreading angle of the wedge, and \( \mu \) is the friction coefficient.

Ohtsubo and Wang (1995) developed a rigid-plastic approach assuming the absence of fracture (which matches with the observation in many tests where there is no crack extending ahead of the wedge tip). Rupture occurs due to ductile failure. The membrane work to stretch the material is integrated over a continuous plastically deforming field near the tip of the wedge. The extent of this membrane stretched plate may be prescribed in the kinematic model based on test observations, or determined using a criterion based on critical rupture strain. The formula for the load-penetration relationship based on this approach is:

\[
F = 1.51 \sigma_0 t^{1.5} \sin^{0.5} \theta (1 + \frac{\mu}{\tan \theta})
\]  

(6)

where, \( F \) is the load, \( \sigma_0 \) is the flow stress, \( t \) is the plate thickness, \( l \) is the tearing length, \( 2\theta \) is the spreading angle of the wedge, and \( \mu \) is the friction coefficient.

The local stretching area near the crack tip is not independent from the “far-field” of deformation where there are two flaps. Geometrically, these two areas are related, and there is not a distinct separating line.
In the analytical models of Eqs. (5) and (6), the local membrane stretching zone and the bending zone of the two flaps are linked through the instantaneous radius of the plastic hinges. Eqs. (5) and (6) were obtained by minimizing the tearing load with regard to this instantaneous radius, a technique commonly used. Again, this leads to the conclusion that the membrane stretching and the plastic bending interact with each other to determine the behavior of the plate structure.

Benchmark studies (Simonsen 1999) have confirmed that these analytical formulae correspond quite well with experiments. Figure 5 shows comparisons of the empirical and analytical formulae with a test on cutting a steel plate 15 mm in thickness.

Many other damage models have been developed, though not introduced. Interested readers can find them from the listed references.
Progressive structural damage model for collisions

The progressive damage process of ship structures follows the possible sequences of failure of major structural members including shell plating and main supporting members (Wang et al. 2000). Longitudinals and stiffeners are commonly treated as smeared thickness, as they are likely to deform with the plates they attached to. Under specific circumstances however, supporting members may also be treated as a smeared portion of shell, which simplifies further the structural modeling (Zhang 2002). Once a global damage model is established, the failure modes corresponding to the behavior of individual structural members are selected and combined together.

As a demonstration, Wang et al. (2000)’s progressive damage model for his test W-50 is introduced. A rigid cone with spherical nose of 50 mm radius was used to penetrate a double hull (Fig. 6). Initially the indenter was pointed at the location of a web girder.

The observed progressive damage process is as the following:

- Stage oa: Load increased rapidly until buckling occurred in the compressed web.
- Stage ab: Load increased rapidly until rupture occurred in the outer skin.
- Stage bc: Rupture initiated in the circumferential direction. Outer skin lost part of its load-carrying capacity.
- Stage cd: Ruptures evolved in radical direction. However load increased until the cone touched the first set of intersections of web girders.
- Stage de: Buckling occurred in the first set of intersections of web girders, followed by continuous crushing of these intersections of plates. Deformation zone of the outer skin expended. Load increased slowly.
- Stage efg: Load decreased slightly.
- Stage gh: The second set of intersections of web girders was actuated too. Deformation zone of outer skin expended further. Load built up again.

The analytical method predicts the damage of the following sequence:

- Stage OA: Shell plate is punched, and the plate punching model (Fig. 3) is used. The web girder is dented locally, and a denting model is used (see Wang 2002).
- Stage A’B: Shell is penetrated and ruptured plate model is used. The web girder is dented locally.
- Stage B’C: Shell is penetrated and ruptured plate model is used. Two intersections of web girders are crushed.
- Stage C’D: Shell is penetrated and ruptured plate model is used. Two intersections of web girders are crushed. Two more web girders are dented.

In view of the complexity in behavior of the double hull, the simplified analytical method predicts very well the progressive damage process and the predicted load follows closely with the test results.

Progressive structural damage due to grounding

There are two loading situations pertaining to grounding of ship bottom structures: vertical loading and loading in the direction of the ship’s length. The former resembles collision loading of side shell and the later is a raking process.

For purposes of analytical treatment of ship raking response, a ship’s hull structure can be characterized as consisting of periodically arranged structural members. For example, going from the bow towards the stern in the longitudinal direction, frames and/or bulkheads occur at certain intervals. As a consequence of the periodicity of such structural elements, a ship’s resistance during bottom raking can also be considered periodic under certain conditions. The load period in such a case starts from one transverse structure and ends at the next transverse structure. A raking scenario may hence be represented as shown in Fig.8 (Wang et al. 1997).
When a rock on the seabed makes contact with a transverse structure such as floors, that structure and the bottom plating immediately behind it interact and can show a very complicated deformation pattern. The transverse frame in such a case fails mainly by in-plane stretching. The bottom plate behind the transverse structure bulges and folds in front of the intruding rock. Usually, many folds are found in that part of the bottom plate. During this damage stage, the internal resistance force of the bottom increases as the rock’s penetration increases. Eventually, as ductile rupture occurs in the over-stretched plates, the resistance force reaches its ultimate value and then begins to decrease. This state of damage can then give way to a different damage process in which the contribution from the transverse structure becomes negligible. Only bottom plate and inner bottom plate (in the case of a double bottom) may then provide resistance against the intruding rock. Usually the resistance force drops to a low level. The bottom plate (including inner bottom) may be
torn open by the rock, steel material within it separates at the part of the plate near the front of the rock. In the wake of the rock, the plate is subjected to load mainly in the lateral direction. It then deflects out of its original plane to avert compression, forming two flaps. A second possible type of damage is the wavy deformation pattern. The bottom plate in this case is peeled at its connection lines with the bottom longitudinal stiffeners or support members. The detached plate then folds in front of the rock. Now if the ship does not stop because it still has unspent kinetic energy, the next transverse structure will become involved in the raking process as well. This marks the end of one so called structural resistance period and the beginning of a new period.

There are four different failure modes used in the analyses. Because of the obvious simplicity in the mathematical expression of these formulae, prediction of the grounding load in a raking accident is very easy to do. The only needed is a common calculator.

Similarly, newly developed simplified analytical methods have been applied to a wide spread of accident situations, including head-on collision on rigid walls, ship-ship collision, ship platform collision, ship-bridge collision, bottom raking, and stranding. Comprehensive surveys of published literature can be found in Ohtsubo et al. (1997) and Wang et al. (2002).

Methods assessing both the internal and external mechanics have also been developed. In these methods, either or both the structural damage and the ship motions are analyzed using simplified analytical approaches. The analyses can be a step-by-step solution of the problems by coupling the internal and external mechanics, or an assessment of energy dissipation in an accident and the energy absorbed by damaged structures that are calculated separately.
SIMULATIONS

The complexities of structural behavior in an accident make it very difficult to generalize conclusions from small model tests. In order to minimize the scaling effects, large-scale tests are often quite necessary. However, performing large-scale tests are prohibitively expensive. FEM simulations have been attempted as an alternative and have been regarded as “numerical experiments”.

Recently, many technical papers have been reported on FEM simulations of collision and grounding accidents of various degrees of complexities (Glykas et al. 2001, Kitamura 2001, Lehmann et al. 2001). These papers demonstrate that non-linear FEM simulations are reliable and provide detailed information. Many powerful special-purpose FEM packages, such as DYNA3D, DYTRAN and PAM, are now available that can account for large deformation, contact, non-linearity in material properties, and rupture.

Useful lessons can also be learned from military, aerospace and automobile industries where simulations of non-linear responses of complex structures have been regularly conducted. For example, FEM simulations have been used to evaluate geometrical stress concentration, large bending of local plates, multi-axial stress fields, time-dependent strain hardening and strain rate effects on material properties, etc.

In general two FEM simulation methodologies are available: implicit and explicit (Moan et al. 2001). Implicit methodology uses the common approach to structural engineering problems (static or dynamic) where the actions are well defined in space and time. Explicit methodology requires solving a system of equations.

For analyzing a collision or grounding accident involving high non-linearity, contact, friction and rupture, the explicit methodology is more suitable. The required calculation efforts are fewer than the commonly used implicit methods. Convergence of calculations is much easier to realize.

Since structures behave in much complex patterns, many special modeling techniques are needed. Challenges involved in analyzing such a high non-linear problem include structural contact, criteria for material’s rupture, crack propagation, among others. At present, only a limited group of researchers have accumulated the major key techniques. Simulations of an accident are still not fully “transparent” to the industry at large.

Compared to FEM analysis for design purpose, simulations of an accident use very fine mesh. An FEM model for accident simulation of a tanker may have 720,000 elements, while the FEM model for the same tanker has only 20,000 elements in a linear elastic analysis. Simulation of a one-second of an accident requires CPU time of about one week, while a linear analysis for design purpose lasts for ten minutes. Figure 9 shows a simulation of a collision accident between a VLCC and a Suezmax tanker (Kitamura et al. 1998). Very fine meshes are used, and the stress and strain distributions around the impact area are obtained to a very detailed level.

How fine the FEM mesh should be at least is an issue under discussions among researchers. Too fine the meshes will only increase the calculation time; while if no fine enough, some failure modes may not be captured and the calculated loads may differ from the reality. Analytical formulations of many structural failure modes such as those introduced in the previous sections can be used to guide the decision of mesh size. These formulae are simple and easy to use, and in many cases give good preliminary estimate of how structural behaviors and how fine the mesh should be in order to capture the localized deformations.
SIMULATIONS VERSUS SIMPLIFIED ANALYTICAL METHODS

Table 1 summarizes characteristics of simulations and simplified analytical methods. This table gives a snapshot about the relative strength of these two groups of methodology. Comparisons of the calculations are based on predictions of a large scale grounding tests conducted by Japanese ASIS (Wang et al. 1997, Kuroiwa 1996).

At this point of time, FEM simulations are more applicable for research purposes, while simplified analytical methods are more practical that may be used in preliminary design stage.

Table 1: Comparisons of FEM simulations and Simplified analytical methods

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Offshore structures

It is in the offshore structural standards that design against accidental loads is formally specified. For example in NORSOK N-001 one of the design objectives is stated as “structures shall be designed such that an unintended event will not escalate into an accident of significantly greater extent than the original event”. In the same standard, for limit state design, accidental damage limit state (ALS) is to be considered along with ultimate limit state, serviceable limit state and fatigue limit state. For ALS design, the structure is to be checked for:

- resistance to accidental action, and
- resistance in damaged condition.

NORSOK N-004 separately provides simplified methodologies for design against accidental loads due to ship collision. It provides, for example, impact force/deformation curves for typical collision scenarios (e.g. 5,000-GT supply vessel against cylindrical structure) and for simple structures such as a beam. The standard requires the damaged installation be checked to verify that its residual strength is enough to withstand the functional load.

Ship Structures

Some classification societies have established requirements to address collision and grounding, in addition to the damage stability requirements.

ABS publishes a Guide (ABS 1995) which provides a methodology for checking the residual strength for ships with collision and grounding damages to ensure that commercial ships have enough strength reserve in case of accidents. A classification notation (RES) will be assigned when such strength criteria are met. To-date a number of tankers carry this class notation.

The RES notation and related guide provides guidelines and assumptions for facilitating an assessment of structural redundancy and hull-girder residual strength, and may be easily employed at an early design stage. After a ship sustains damage in the prescribed most unfavorable condition, a minimum residual strength of hull-girder is to be maintained with regard to preventing, or at least substantially reducing, the risk of a major oil spill or loss of ship due to a post-accident collapse or disintegration of the hull during tow or rescue operation.

Germanischer Lloyds has a classification notation, COLL, which ranks the resistance of a vessel against a pre-defined set of collision scenarios. Unfortunately, no ship as yet carries this notation.

Hitherto the concern with survivability in the event of an accident has been on loss of stability or buoyancy, or the outflow of polluting liquid cargo, or both. Thus, considerable volume of regulatory requirements have been promulgated on subdivision and damage stability, as is prevalent in Safety of Life at Sea Convention (SOLAS), the Loadline convention, and the International Convention for the Prevention of Pollution from Ships (MARPOL).

In the continued quest to improve maritime safety and environment protection, there has been tremendous interest in evaluating existing designs and developing new designs in light of tankers’ ability to provide greater protection against oil spill during collision and grounding with more efficient use of structure (Ohtsubo et al. 1997). Improving the structural crashworthiness proves to be a very efficient means, and the related researches and investigations have produced many valuable insights and useful hints about how and to what extent damages may be minimized.

Kitamura (1996) did an extensive study by using non-linear FEM simulation techniques in comparing some designs of side structures. He found that the differences in energy absorption capacity of conventional double side design variations are limited. Updating steel material is effective and efficient because the design alternation does not result in a net steel weight increase or expansions of ship dimensions. Excessively large fillet welds connecting side shell with the main web structure may result in early rupture.
Simplified methods are well suited for parametric studies and have been used to investigate the influences of design changes (Paik et al. 1999, Tikka and Chen 2000). Paik et al. (1999) calculated the variation of collision energy absorption capacities of a double hull VLCC changing thickness of shell plate, inner skin, side stringer and transverse, width of wing ballast tank, and material. Studies like this provide useful information with which a designer can use for improving his design against possible accidents.

CONCLUSIONS

This paper presented a framework for a standard for ship structure design against accidents. One of the key components of such a standard is the methodology for predicting the behavior or the response of ship structures when met with an accidental load. Two approaches were presented: simplified analytical method and non-linear FEM simulation method. For simplified analytical method, much research is still on-going. This paper presented some useful results, from discrete phenomena modeling such as plates under large impact load, plate rupturing and plate tearing, to progressive structural damage modeling. Non-liner FEM methodology is briefly described with a view to shed light on its limited practicability for structural design purposes.

Design against accidental loads has been a practice for offshore structures for some time, but is not fully established for ship structures. The high variability in accident frequency and in severity of the impact load may have discouraged any attempt in setting a standard. Equally important, the relative lack of analytical methods to predict ship structure behavior during an impact may also have hampered the development of such a standard. As this paper has shown, with improving ability to predict ship structure performance in accidents, and increasing desire to enhance ship safety and environment protection, the realization of such a standard may well be in the not too distant future.

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