Behavior analysis of container ship in maritime accident in order to redefine the operating criteria

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Abstract. In order to enhance the efficiency of maritime transport, container ships operators proceeded to increase the sizes of ships. The latest generation of ships in operation has 19,000 TEU capacity and the perspective is 21,000 TEU within the next years. The increasing of the sizes of container ships involves risks of maritime accidents occurrences. Nowadays, the general rules on operational security, tend to be adjusted as a result of the evaluation for each vessel. To create the premises for making an informed decision, the captain have to be aware of ships behavior in such situations. Not less important is to assure permanent review of the procedures for operation of ship, including the specific procedures in special areas, confined waters or separation schemes.

This paper aims at analysing the behavior of the vessel and the respond of the structure of a container ship in maritime accident, in order to redefine the operating criteria. The method selected by authors for carrying out the research is computer simulations. Computer program provides the responses of the container ship model in various situations. Therefore, the simulations allow acquisition of a large category of data, in the scope of improving the prevention of accidents or mitigation of effects as much as possible. Simulations and assessments of certain situations that the ship might experience will be carried out to redefine the operating criteria. The envisaged scenarios are: introducing of maneuver speed for specific areas with high risk of collision or grounding, introducing of flooding scenarios of some compartments in loading programs, conducting of complex simulations in various situations for each vessel type. The main results of this work are documented proposals for operating criteria, intended to improve the safety in case of marine accidents, collisions and groundings. Introducing of such measures requires complex cost benefit analysis, that should not neglect the extreme economic impact that may result from such casualties.

1. Introduction
As shown in the European Maritime Security Agency Report - EMSA 2015, between 2011 and 2014, from the total of 4620 accidents, in 787, i.e. 17%, are involved container ships. After the general cargo (34%), container ships are in this ranking of specialised vessels accidents prior to bulk carriers and tankers (13%) and (9%). As the nature of accidents during the same period, the grounding represents 17% (after losing control-24%), having the same rate of incidence with collision and contact (17% each) [4].

Increasing size of the ships is a component of container transport sector. There are already 19,000 TEU vessels in operation and 21,000 TEUs ordered but size vessels growing involves risks accordingly. As the AGCS report shows, over 50% of compensation over 1 million are due to grounding accidents.
Major exposure not only refers to cargo or the ship but also the environment, aspects of social or economic nature [3].

Until recently, oil pollution was the main concern in case of tanker vessel’s grounding accidents, but related aspects of damage to the hull, that alter the stability of the ship, starts now to become a constant factor in the field of maritime research of this accident type and the implications it has for all other ships. Grounding of a container ships brings new challenges, in particular for vessels with a length exceeding 300 m; size involves of a considerable number of containers that can be damaged, increased numbers of means for refloating, port of refuge for damaged ship, to name a few.

Also, the loads on the resistance structure of the vessel are considerably higher, leading to its weakening or even loss of the ship, due to major deformation or breakage the structure. Disasters caused by shipping casualties were immediately led to new requirements, in terms of design and construction of the ship, such as double bottom for oil tankers (following the accident the ship EXXON VALDEZ) or improving of the operational procedures (due to grounding of passenger ship Costa Concordia, all procedures for bridge team were changed). Currently, the general rules regarding operational safety, tend to be adjusted as a result of safety assessment for each ship. The key issue to assess operational safety of the ship is the likelihood and consequences of a potential accident, these issues taking account of the ship's characteristics, area of operation etc. They have already been developed and are continually improved assessment methodologies, including failure maritime accidents, as part of the probabilistic risk analysis [1].

In risk analysis accident that resulted in ship’s grounding, is necessary to define the relationships between input parameters - speed of vessel, hull shape, seabed nature etc., and size of the damage. Because similar collision tests, as in industrial domain, cannot be achieved due to the evident costs and the vessels are built in series relatively small, compared to other means of transport, and reduced testing scale not have the accuracy needed to obtain valid results, the simulating of these accidents remain the only option. Simplified models of groundings have been achieved and improved over the past decades and were completed successfully by numerical simulation, with the development and introduction of computing accuracy of input parameters as the extremely varied approach of an accident. The finite element method (FEM) is increasingly used, and it is widely accepted in all stages of ship design but also in its operation in various situations. The results obtained from the research vessel behavior with finite element method and its analysis, the variety of situations and accuracy of responses, can form the basis of a modern approach to improve the safety of the ship.

2. Ship’s grounding accident analysis

Ship’s grounding risk assessment involves analyzing the factors that can lead to this type of accident has consequences that failure and the link between all components involved in the process. It is required an exhaustive analysis of accidents that result in grounding of the ship, in order to issue concrete proposals to improve safety in container ship operation.

They obviously need to be evaluated in cost benefit key, for effective implementation in maritime domain.

Ship’s grounding accidents are common for all ships but, for container ships, specific are highlighted in the factors contributing to such accidents, risks associated with the type of vessel and the steps to be taken following the analysis of events. They obviously need to be evaluated in cost-benefit key for the effective implementation in the maritime field.

The grounding of ships, can be divided into two main categories, given the nature of seabed which has direct consequences for the results of accidents and can be:

- Grounding on „soft” seabed – sand, mud, small gravel – produces relatively small damage to hull plates but, may induce bending moments and shear forces, which can lead to weakening or rupture of the ship’s structure;
- Grounding on „hard” seabed – rock – more or less homogeneous, which produces rupture of the hull plates and destroying or weakening of strengthening elements, induces shear moments but also flooding of ship’s compartments.
However, there are recent additions to this classification, which include the "reef" typology seabed in order to frame many types of interaction between the hull and the seabed, as shown in figure 1.

![Grounded on rock, Grounded of reef, Grounded on Shoal](image)

*Figure 1. Ship’s grounding on various seabed (Alsos and Amdhal, 2007).*

They were also introduced new concepts, such as "sliding", by Alsos and Amdahl in 2008, to study the grounding on the soft seabed, when the bottom suffer denting rather than tearing deformations on large surface, or " raking ", by Wang in 1997, when the hull, due to contact, is unveiled by the rocky bottom of the sea. Current approaches investigate the overall strength of the hull, due bending moments, in case of grounding on soft bottom (larger surface) and bottom plates cutting or tearing, due to grounding on the rocks. In this case, due to small contact area, shear forces occurring in the hull and study of local stress is also developed [4].

2.1. *Container ship grounding on soft seabed*

In the first phase, the ship is subjected to an impulse, which is considered inelastic in contact with the ground. In the second phase, the ship slides on the ground, being in continuous contact with it. The kinetic energy remaining after the first stage is converted to potential energy applied to the contact surface of the vessel (subject to friction) and soil deformation, when it is soft [3].

The ship will furrow seabed, depending on the speed and shape of the bow, and if is a container ship, both are favorable to a strong grounding. For theoretical analysis, numerical integration can solve the field equations for the motion of the ship or a simplified approach based on conservation of energy and momentum, a section of the hull form [5]:

\[
\bar{p}_i(x) = \frac{\partial \bar{B}}{\partial t} - \bar{\omega} \times \bar{B} \\
\bar{m}_i(x) = -\frac{\partial \bar{I}_0}{\partial t} - \bar{\omega} \times \bar{l}_0 - \bar{U} \times \bar{B}
\]  

(1)

Where, \(\bar{p}_i\) and \(\bar{m}_i\) are the inertia force and inertia moment, applied at the centre of gravity of the hull segment \((x,y,z)=(x,0,0)\), \(\bar{B}\) and \(\bar{I}_0\) are the translational momentul and angular momentum vectors, \(\bar{U}\) is the translatory velocity of the section and \(\bar{\omega}=(0,\Psi,0)\) is the instantaneous velocity of rotation of the segment about the instantaneous axes of the moving coordinate system, see figure 2.
Figure 2. Ship grounded on soft seabed.

The ship hull is considered as an elastic beam (Timoshenko model), which allows lifting a section of the body due to the efforts to end. Soil reaction is given by the pore water pressure on the bow, p, can be determined from formula:

\[ p = \frac{\varphi}{U_b} k \]  

(3)

where

\[ k = \frac{\rho_w (1+e)}{e} U_b + \frac{\rho_w g}{k_e} U_b \]  

(4)

and:

- \( \varphi = \varphi(x,y,z) \) the pressure associated with the motion of the rigid bow into ideal fluid,
- \( U_b \) and \( \dot{U}_b \) hull velocity and acceleration in the saturated soil, respectively,
- \( e \) the void ratio (pore volume/grain volume),
- \( \rho_w \) the water density,
- \( k_e \) an effective soil permeability coefficient,
- \( g \) the acceleration of gravity

Integration of the pressure p over the surface of the bow gives the total force component (Xpore, Zpore).

The pore water force \( F_R \) in terms of the added-mass coefficient \( C_m \) is:

\[ F_R = C_m V_R k \]  

(5)

where, \( V_R \) is the soil volume displaced by the ship bow. There are tabulated values of added-mass characteristics \( C_m V_R \), for many geometrical shapes of bows [5].

Container vessels have a high sea speed, more than 20 kts, so, on a soft seabed accidental grounding, caused fortuitously, may result in a large portion of the hull lifted, which induces important loads over the structure. In order to achieve this high speed, the resistance of the hull needs to be minimized, which is obtained by a fine form hull, but became a dangerous factor because it induces shear and bending moments (M, Q in Fig. 2) supplemented by the great length of such vessels. In case of grounding with slow speed, there is a major advantage in hull integrity and refloating manoeuvres which are greatly simplified.

2.2. Container ship grounding on rock

The characteristics of the container ship grounding on rocks or rock can be considered as follows:

- contact surface between bottom of the ship and seabed is relatively low;
in the initial phase, the kinetic energy is dissipated in structural energy but, may damage the ship structure in the next period after incident;

there is a great possibility to break the hull and in this case the stability of the ship is affected, more or less, depending on number of flooded compartments;

the refloating maneuvers are hampered because usually the ship remain stucked on the rock and any maneuver could produce more damages to the structure;

if the ship is "suspended" on the rock, a small change of position (caused by waves, tides, weight’s changing on board of ship), and small areas of action of forces on the hull, may induce strong shear moments, so, period as the vessel remains in same position is critical (see figure 3);

ship heel due the flooded compartments could force the lashings and cause the fall over board of containers.

Approach of this type of accident, as was shown above, is by studying the internal mechanics. Most recent studies on accidents resulting in grounding of the vessel, focused on assessing the grounding forces and deformation energy.

The simplified methods of analysis use the theoretical formulations and take into account processes occurring in damage to the structures. These methods are tools for designers and give the perspective of local and global processes occurring, providing their prediction with high accuracy. However, the method has limitations in assuming certain theoretical assumptions, which not in all cases describe with great accuracy, the complexity of the hull structure (the welds, reinforcements, stiffeners etc.), but is strongly promoted by research organizations in this field [2].

The studies have been focused on several models related to the behavior of the bottom plate and the framing elements of the vessel in extreme situations, such as deformation and tearing of metal plate, cutting, bending or folding [7].

Because in the above-mentioned research, is analyzed the behavior of the ship’s structure elements, the theoretical basis is mostly taken from the theory of plastic deformation.

To study the damage caused by penetration of the hull over a certain length and a certain depth of penetration (see figure 4), is proposed a simplified formula, showing the dependence of the form of the rock; the rock shape is a parabola [3]:

\[ z = \frac{y^2}{a} \]  

The pressure of contact between ship and rock \( i, \) rock \( a, \) to a penetration depth \( \delta, \) can be obtain with expression:

\[ p(a, \delta, h_{DB}) = \frac{F_H}{A} \]  

where \( F_H \) is the horizontal grounding force, and \( A \) is the contact area which depend on penetration depth.
\[ A(a, \delta, h_{DB}) = \begin{cases} \frac{4}{3} \sqrt{a} \delta^{\left(\frac{3}{2}\right)}, & \text{for } \delta \leq h_{DB} \\ \frac{4}{3} \sqrt{a} \left[ \delta^{\left(\frac{3}{2}\right)} - (\delta - h_{DB})^{\left(\frac{3}{2}\right)} \right], & \text{for } \delta > h_{DB} \end{cases} \]  

(8)

Another approach of grounding through simplified analysis method is in regard to tearing resistance study of the bottom plate in contact with a wedge cutting surface [6]. Simple formulae have been developed to simulate this mode of response, for example by Zhang in 2002, such as:

\[ F_R = 1.942 \cdot \sigma_F \cdot t^{1.5} \cdot l^{0.5} \cdot \varepsilon_R^{0.25} \cdot \sqrt{\tan \theta} \cdot (1 + \frac{\mu}{\tan \theta}) \]  

(9)

where: \( \sigma_F \) is flow stress, which is taken as the average of the yield and ultimate stress, \( t \) thickness, \( l \) tearing length, \( \varepsilon_R \) uniaxial rupture strain, \( \mu \) friction coefficient (value between 0.3 and 0.4), \( \theta \) half angle of wedge shaped tearing object (conical shape considered).

3. The use of MEF for ship’s grounding analysis. Numerical simulation of grounding response

For ease of application compared to theoretical models and quantity of information needed of work, internal mechanical analysis and numerical simulations of groundin response may be performed by using FE codes for such incidents. One of the actual approach is to study the failure criterion of the material and the simplest way to account it is to define the Mises strain limit which result from FEM. Because material properties subject to deformations are not linear, the non-linear FEM analysis provides the most detailed and reliable results and such a program is NASTRAN used by NX SIEMENS. In a simplified simulation using the Unigraphics NX 8.0, based on the formability of the material of ship bottom, it can be determined the shear, normal and von Mises stresses. Once the stresses are computed, could also be determined the fatigue life, strength safety factor and fatigue safety factor.

It was considered a Panamax vessel grounded on soft seabed (sand, mud), and was studied the response of the material in the bottom zone and bilge zone due grounding pressure. (see figure 5).
The area of study was chosen between frame 123 and 133 (see figure 6), plate material is considered isotropic steel SZ35JR-EN 10025. After the first zone was meshed, was obtained 8747 CTETRA elements and 17149 nodes and various loads was applied. (see figure 7).

For the second zone, after meshing, resulted 8582 CTERA elements and 16834 nodes, represented in figure 9. Same loads was applied and obtained the normal stress with diagrams and von Mises stress and diagrams obtained (see figures 10-14).
The deformation pattern for different values of stress is revealed as a result of simulation. To obtain results that help to realization of measures, it needs more simulations for ships of different sizes and areas affected. Useful conclusions may be drawn from inspection at damaged ships suffered grounding accidents.

4. Conclusions
The most important parameters used in numerical simulations of a grounding ship are: kinetic energy dissipated in structure, which depend on speed and displacement, and penetration depth, which depend on speed, hull form, angle of grounding and seabed nature and form.

The above parameters induce results affecting ship – ultimate strength, buoyancy or cargo – containers fallen in water, damaged or destroyed. Another affected side could be the marine environment – oil spill pollution, or port structures – bridges, breakwaters, quays etc.

The goal is to define some acceptance criteria, including: the ship speed above critical event could happen, the angle of collision, trim of vessel, draft for the worst scenario, the allowable quantity of oil in double bottom tanks, and the minimum value of hull strength.

The measure to be taken can impose restrictions on the design and operations to keep the consequences of adverse events below some limits. Port authorities should be interested, after a cost benefit analysis, to encourage various studies and research, in order to minimize the risk or reduce the impact of a result of such accidents.

5. References

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