PARAMETRIC STUDY OF THE DAMAGE INDUCED IN SHIP COLLISION IN THE ADRIATIC SEA

Abstract

Adriatic Sea has a relatively small surface and it is only by the Otrant straight connected with the Mediterranean Sea. Oils or other dangerous cargo spill would therefore have a catastrophic and long-term consequences. The announced construction of teh LNG terminal, research and future exploration of carbohydrates, as well as the increase of maritime traffic due to a rising demand for the energy, increase the risk of ship collision in the Adriatic Sea. In order to review a problem of the ship damage in such event, a scenario of a collision between a ferry and a tanker is assumed and considered as a typical for the Adriatic. A detailed analysis of collision consequences is performed using non-linear finite element method. Then, a parametric study of the damage is done: in comparison with the reference model, a ferry impact speed, their size and mass and the impact angle is varied. For each of this cases the outcome is analyzed, with an accent on the damage and breach of the tanker inner hull. Finally, the dependency of the damage level upon the particular collision parameter is presented.

Key words: ship collision, non-linear FEM, parametric study, inner hull breach

PARAMETARSKA STUĐIJA OŠTEĆENJA PRILIKOM SUDARA BRODOVA U JADRANSKOM MORU

Sažetak


Ključne riječi: sudar brodova, nelinearna analiza MKE, parametarska studija, oštećenje unutarnje oplate
1. Introduction

Ship collisions and groundings are marine accident of rare occurrence but of significant consequences: loss of life, environmental pollution, significant ship damage and costly repairs etc. Unfortunately, ship collisions are still unavoidable due to a number of reasons. Of a number of the historical collisions one of the most famous one was RMS Titanic collision with iceberg in the North Atlantic in 1912 when more than 1500 people died. After that disaster, but also after a number of other similar events, both public and professional awareness of the problem arose and more strict regulations and measures were put in force to prevent such events to occur in the future. Due to that, there is a constant decrease of a number of marine accidents in the sea.

However, collisions with catastrophic events still occur. One of the most tragic event occurred in 1987 when "MT Vector", carrying 8800 barrels of gasoline collided with "MV Doña Paz". The impact caused a fire that quickly spread to "Doña Paz", as well as putting the surrounding water surface on fire. With an estimated death toll of 4,375 people this incident resulted in the deadliest ferry disaster ever and the biggest recorded in history during peace time.

Another, more recent event, is a good example of collision made by human mistakes. "Costa Concordia", an 8 year old modern large cruiser carrying 4,252 people deviated from its course near the Isola del Giglio and struck a rock formation on a sea floor on January 13th 2012. As a result of the damage "Costa Concordia" gradually sloped on the starboard side. Fortunately, it grounded at the nearby coastline and almost all of the people were safely evacuated. Still, 32 people lost their lives because they were trapped on board after the overthrow. The "Costa Concordia" was one of the 121 total-loss incidents recorded that year.

When marine environment pollution is considered, particular attention should be paid to ship collision consequences in small and closed seas such as the Adriatic Sea. Ship traffic in Adriatic Sea is in constant increase. Recent plans for building the LNG terminal in North Adriatic, growing demand for oil supply and announced activities in carbohydrate exploration in the Adriatic indicates that marine traffic in that area will further increase. Consequently, the risk of marine accidents, including the ship collisions will also increase.

Within this paper a representative ship collision scenario for the Adriatic Sea examines and Aframax tanker and a passenger ferry collision, where ferry hits the tanker amidships in a reference study case. Furthermore, several collision parameters, such as the mass and speed of the striking ship were altered to study the effect of each parameter to collision consequences, in particular the inner hull breach. Significant values of energies and contact forces from are obtained and a comment on the performed parametric study is presented.

2. Rules and Regulations

A common first step in dealing with marine problems is to consider Rules and Regulations. However, in the case of ship collision the matter is not straightforward. Due to the low probability of occurrence and complex dynamics of collision events, as well as a great number of parameters considered, Classification Societies cannot create dedicated regulations.

DNV [1] considers simple deterministic approach: the hull size has to be able to absorb the energy created as a result of ship collision, without the rupture of the crude oil tanks. The kinetic energy is not to be taken less than 11MJ for sideways collision and 14MJ for stern or bow collision with 40% of added mass for the struck ship and 10% for striking ship.

A different approach is taken by GL [2] where instead of the measurement of the collision energy, a critical collision speed is defined: it is a speed at which the bow of the striking ship hits the side shell of the struck ship. The aim of this approach, that may be considered probabilistic, is to standardize collision cases referencing to the critical speed.
IMO is specific in its criteria for the damage, as regards the position of the cargo tanks and the width of the double hull [4]. In the IMO codes, dangerous cargo is recommended to be located at a minimum distance from the side shell of 0.76m. Rupture or damages are to be limited to 20% of the ship’s breadth. In 1992 Marine Environment Protection Committee (MEPC) of IMO agreed that oil tanker must have a double hulled structured or equivalent alternative. The minimum hull depth required is 2m.

ABS [4] ship collision evaluation is based on risk assessment. ABS risk assessment evaluation procedure defines the assessment inputs: collision scenario definition, structural configuration, material properties and applied loading.

According to ABS, there are three methods to determine the strain energy in the facility and colliding vessel, Fig. 1:

- Method A - rigid body colliding with the facility (Af). It is assumed that the entire change in kinetic energy is accounted for by facility deformation. This is the most conservative of the three alternatives and will indicate the most severe facility damage.
- Method B - two independent analyses considering a rigid body colliding with the facility (Bf) and a deformable colliding vessel impacting a rigid facility (Bv). This is less conservative than the first approach as it includes the strain energy from the colliding vessel with the facility. While the damage curve for the facility is unchanged from the first approach, the total applied load may be significantly less.
- Method C - Coupled analysis of a deformable facility (Cf) and colliding vessel (Cv). This is the least conservative of the three, but the most computationally expensive, as it not only accounts for strain energy developed in both bodies but also considers the effect of impact force being spread out over a larger area as the two bodies deform. This method is employed in the present paper using commercial software package LS-Dyna.

![Fig. 1 Three alternative approaches to predicting facility and colliding vessel strain energy](image)

*Slika 1. Tri alternativna pristupa predviđanju energije deformacije objekta i broda u sudaru* [4]

### 3. Adriatic Sea collision scenario

Adriatic Sea basin is a semi-enclosed narrow sea solely connected to the rest of Mediterranean through the Strait of Otrant, which is at the same time the narrowest part of the Adriatic Sea. The northern and north-western coastlines are characterised by shallow waters and sandy beaches at the west side. The eastern part is deeper, rocky and contains many islands and islets. The deepest part of Adriatic is located in the south. Although the Adriatic Sea is not large it cannot be considered as calm sea: predominant northern winds like Maestral (NW) and Bora (NE)
can have hurricane strength while southern winds (SE) can generate large fetch and dangerous sea conditions.

The Adriatic Sea is an important maritime transport route used by merchant ships in international and national trade and by yachts, fishing vessels and other non-merchant ships. Such traffic is implying a significant risk of accidents and consequently a potentially strong impact on the marine environment. Given the enclosed nature of the Adriatic Sea basin, the impact of a single accident, even though accidents are rare, can be highly disastrous. Fig. 2 presents the zones of highest risk for ship collisions (in red, figure on the left) and the overview of the marine traffic in 2008, that may be considered typical for Adriatic [5].

![Fig. 2 Highest collision risk zone (red) and marine traffic in the Adriatic in 2008 [5]](image)

The highest risk of collision occurs in the northern Adriatic where several large harbours are located (Trieste, Venice, Koper, Rijeka) upon which mid-European countries heavily depend on for the import of energy and other goods, but also at the location of intersection of the main cargo routes running from the north-west to the south-east and the main international ferry and leisure routes running from the west to east coast of Adriatic, as can be seen on Fig. 2 (right).

Due to that, the most probable collision scenario that could occur is the one of a cargo ship and a ferry ship. The situation during the impact will vary but is reasonable to assume that the bow of the ferry hitting the tanker cargo hull nearly or exactly orthogonally would create most catastrophic consequence: oil spill can easily occur and a risk of fire exists, that can endanger the lives of both ships. The main consequence of such impact, beside the risk of the loss of life, is the cargo spill.

4. Case study – tanker and a ferry collision

In order to set up a calculation model in LS-Dyna models of both struck and striking ship have to be generated and then calculation parameters such as the model speed and boundary conditions defined.

An Aframax tanker is considered as a struck ship. An Aframax ship is an oil tanker smaller than 120,000 metric tons deadweight (DWT) and with a breadth above 32.31m. This kind of ship doesn’t have a complex design and due to the significant displacement majority of structure in full condition is on the wet part. Main ship particulars for both struck and striking ship are listed in Table 1.
Table 1 Main struck and striking ship particulars

<table>
<thead>
<tr>
<th>Struck ship (tanker)</th>
<th>Striking ship (ferry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lpp</td>
<td>Length over all</td>
</tr>
<tr>
<td>B</td>
<td>Ship mass</td>
</tr>
<tr>
<td>D</td>
<td>Ship with cargo mass (assumed)</td>
</tr>
<tr>
<td>Scantling draught</td>
<td>Draft aft</td>
</tr>
<tr>
<td>Displacement</td>
<td>Draft fore</td>
</tr>
<tr>
<td>Max. service speed</td>
<td>Middle draft</td>
</tr>
<tr>
<td>Ship center of gravity by length (from L/2)</td>
<td>Ship centre of gravity height</td>
</tr>
<tr>
<td>Ship center of gravity height</td>
<td>Ship centre of gravity length</td>
</tr>
</tbody>
</table>

Since fine mesh is required in the collision zone entire ship is not considered. Instead, half of the three cargo holds up to the centreline are defined, namely bow, central and aft cargo holds, Fig. 3. The origin of the global coordinate system is located at the bow bulkhead of the central cargo hold. The model consists of 82 different finite element properties that include 29 plate element thicknesses and 14 T-section, 5 L-section and 15 flange-section beam properties and three different steel properties, namely AH32, AH36 and ST24 steel.

Fig. 3 Struck ship model with collision zone indicated by red lines (left) and refined model (right)

Slika 3. Model udarenog broda, zona sudara označena crvenim linijama (lijevo) i rafinirani model (desno)

Fine mesh collision zone encompasses the volume of approx. 24.96x12x21.1 m³ and is generated by finite elements having the average size of 100x100 mm. All the beam elements in the collision zone are modelled with plate elements. Particular attention is paid to the transition zone from the fine mesh to the coarse mesh so that elastic deformation outside of collision zone is possible. The remaining mass of the entire ship is accounted by additional rigid finite elements constrained to the centreline nodes so that the mass of the rest of the ship is constrained to move with the mass of the three cargo hold models. Location of the solid elements is calculated precisely so that total struck model centre of gravity remains exact.

A typical ferry operating in Adriatic Sea on international route is selected as a striking ship. The main particulars of the ferry are presented in Table 1 while the finite element model, along with
tanker model, is presented on Fig. 4. The bow of the ferry is modelled using plate finite elements while the rest of the ship is modelled using beam elements with appropriate stiffness and mass. Since only bow deforms during the collision the striking ship model is simplified in a described way. More details about ferry finite element model may be found in [6].

Finally, reference model collision set-up is presented in Fig. 4 where a location of a striking ship vs. struck ship is visible.

Fig. 4 Reference model collision set-up
Slika 4. Referentni postav proračunskog modela sudara

5. Collision scenario parameters

Unpredictability of ship collision makes the problem analysis difficult. There is a number of collision possibilities that may occur in reality and it is difficult to consider them all. However, certain main parameters may be taken into account and varied during the analyses. The following scenario lists the reference collision scenario parameters:

- Ferry is located in front of the middle cargo hold of a tanker,
- Collision is orthogonal,
- Speed of a tanker is 0 m/s,
- Speed of the ferry is 8 m/s,
- Draft of the tanker is 15.1 m,
- Draft of the ferry is 5.3 m.

The main purpose of this article is to explore behaviour of the ships in collision event for different collision parameter variation. The large quantity of variables involved in the process could generate endless situations making this topic very hard to face. Therefore, only most important parameters are selected and their variation is taken into account separately. In another words, only one parameter is changed in each collision calculation, while all the other parameters are maintained equal to the ones in reference scenario. Following principal parameters were varied:

- Ferry speed variation,
- Tanker draught variation,
- Impact location variation,
- Impact angle variation,
- Scaled striking ship length/mass variation.
The speed is one of the most important collision parameter as it increases, with the square power, the striking ship kinetic energy. Hence, a variation of speed involves a significant variation of collision energy. Following striking ship velocities were considered: 2 m/s, 4 m/s, 6 m/s, 8 m/s (reference model), 10 m/s and 12 m/s. The reference speed is a sailing speed of a ferry in concern. The lower speeds may be obtained by slowing down the ferry during the evasive manoeuvre. Higher sailing speeds may occur in the case of faster similar size ferry.

Draft variations occur during different operation conditions and are related to the amount of the cargo loaded, density of the cargo and other factors. Assuming one standard tanker ship all the operational conditions can be analysed. Following tanker drafts are considered: 7.5 m (ballast), 11 m (partial load), 13.1 m (full load, low cargo density), 15.1 m (reference model) and 15.7 m (full load, high cargo density).

Impact location is a parameter related to the location of contact. As only three cargo holds are modelled and just a middle one with fine mesh, the ship mass element was shifted in order to simulate collision with one cargo hold more to the bow and one cargo hold more to the aft. By shifting the mass elements properly and away from the ship's centre of gravity, a generation of naturally occurring momentum is allowed during collision. Following locations of ship mass are considered: \( x=49.737 \) m (aft cargo hold collision), \( x=19.017 \) m (reference model), \( x=-11.703 \) m (bow cargo hold collision).

Angle variation considers non-orthogonal collision event. The collision angle is defined as the angle between the velocity vector of the striking ship and struck ship longitudinal axes. According to [7] historical records indicate no preference of one collision angle over another. In other words: chances for any collision angle to occur are nearly equal. Following collision angles were considered: \(-45^\circ\), \(-30^\circ\), \(-15^\circ\), \(0^\circ\) (reference model), \(15^\circ\), \(30^\circ\) and \(45^\circ\).

To take into account the possibility of larger and smaller ferry to collide with selected tanker, ferry model was scaled up and down, respectively. While scaling of the size is straightforward as considers only geometrical scaling, scaling of the mass requires careful consideration. At first, following ferry lengths are selected: 100 m, 128 m (reference model), 150 m, 175 m and 200 m. Upon the data found in [8] and [9] a relation between the ferry length and ferry mass, for different ferry types, is established and illustrated in Fig. 5. A trend-line could be established from the collected data and used to determine approximate mass of a ferry for a given length. Out of this analysis following ferry masses were obtained, with respect to the lengths listed above: 4251 t, 6889 t (reference model), 13226 t, 23329 t and 41149 t.
6. LS-Dyna calculation model considerations

Setting up the calculation model requires certain amount of skill and continuous verification of the stability of calculation and the reliability of results. Collision analysis is performed by non-linear finite element explicit time domain analysis involving contact problem and non-linear material model in commercial software package LS-Dyna. Following main considerations describe the analysis set-up.

Contact between the striking and the struck ship is defined using LS-Dyna keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE which enables contact between each and every part of the model. This refers to the sophisticated algorithm that evaluates contact between both outer and inner surface of each finite element during the collision. Both static and dynamic friction is defined for steel-to-steel situation and chosen values are 0.74 and 0.57 respectively.

Reduction of hourglass effect is done by application of fully integrated shell element formulation. Hourglass effect is a numerical instability resulting in unrealistic deformation energy for a reduced integration point elements, when the nodes are changing position while the length of the element in the main axis of integration remains the same, resulting in a mesh with "hourglass" appearance.

Material models used are defined by keywords *MAT_PIECEWISE_LINEAR_PLASTICITY and *MAT_ELASTIC. The former one is used for all the elements in collision zone and on the striking ship bow, while the latter is used for all the other finite elements, including the striking ship hull beam elements. Non-linear material properties are obtained by experiment on Grade A steel and are given in LS-Dyna as a set of true stress-strain points.

Mesh size parameter is taken into account by applying Peschmann method of correcting the failure criteria, i.e. critical strain, depending on the finite element size and thickness. For each model part thickness and a chosen standard length of 100x100 mm in collision zone, a Peschmann correction is applied and critical strain calculated. This is an essential step in the ship collision analysis as effectively reduces the excessive deformation energy occurring from the unrealistic deformation of large finite elements.
7. Analysis of the results

Due to a large number of simulations performed an overview of the analysis results should be given first. Collision simulation is first performed for the reference model in order to check the stability of calculation and overall behaviour of models. As it was said earlier, reference calculation model includes orthogonal collision of a standard ferry with a cruising speed of 8 m/s and a motionless fully laden tanker.

Due to reference model collision, damage in tanker hull occurs, as presented in Fig. 6. As it can be seen on Fig. 6, at time instance \( t = 2\) s ferry has breached the inner hull of the tanker and the overall damage on its hull is significant, with a large plastic deformation zone.

![Fig. 6 Reference model collision: situation (left) and plastic strain (right) at \( t = 2\) s](image)

Slika 6. Sudar – referentni model: pozicija brodova (lijevo) i plastična deformacija (desno) u \( t = 2\) s

Two most important collision data available are collision energy and contact force. Former one provides information about the energy lost for elastic and plastic deformation of finite elements and is denominated Internal Energy in LS-Dyna. The latter is a measure of force occurring during the contact between two ships and is measured automatically by the software. Time domain graphs of all the energy components and contact force are presented in Fig. 7.

![Fig. 7 Reference model: model energies (left) and contact force (right)](image)

Slika 7. Referentni model: energije modela (lijevo) i kontaktna sila (desno)

Following can be observed from Fig. 7. Internal energy is equal to zero at the start of calculation and starts to increase only when contact between ships occur. Internal energies of both ships are included in the graph i.e. elastic and plastic deformation of both ships is taken into
account. By looking at the contact force graph, one can notice that contact force increases during the penetration of the ferry bow in tanker hull until a maximum is reached. Then, contact force decreases as both ships obtain the resulting joint movement speed. This is a moment when most of the available kinetic energy is transferred into other forms of energy: mostly energy of elastic and plastic deformation, but also on friction. The sliding energy is the sum of the normal (contact) energy and the shear (friction) energy. Information about the numerical loss of energy, namely hourglass energy may be obtained, and in this case it is less than 1% of total energy which is acceptable. The initial and final energy components, as well as maximum contact force are enlisted in Table 2. Now, all the other collision scenarios can be analysed in a similar way and compared.

Table 2 Reference model - Initial and final energies

<table>
<thead>
<tr>
<th>Reference model</th>
<th>Initial total energy</th>
<th>[MJ]</th>
<th>216</th>
<th>Max. internal energy</th>
<th>[MJ]</th>
<th>165</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final total energy</td>
<td>[MJ]</td>
<td>254</td>
<td>Final internal energy</td>
<td>[MJ]</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Initial kinetic energy</td>
<td>[MJ]</td>
<td>216</td>
<td>Hourglass energy</td>
<td>[MJ]</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Final kinetic energy</td>
<td>[MJ]</td>
<td>14.6</td>
<td>Sliding energy</td>
<td>[MJ]</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Initial internal energy</td>
<td>[kJ]</td>
<td>0.0</td>
<td>Contact force</td>
<td>[kN]</td>
<td>6600</td>
<td></td>
</tr>
</tbody>
</table>

Due to the large number of simulation only the summary of the results will be presented. For all the collision scenario, the internal energy is considered to be a most important parameter and maximum internal energy for each parameter variation is presented in Table 3. Results should be interpreted as follows:

- Hull breach case – red color,
- Internal hull damage – yellow color,
- No damage on internal hull – green color.

Other than this, numbers indicate the kinetic energy lost during collision for all the parameters variation, i.e. speed, draft, impact location, angle variation and mass/length variation.

Table 3 Maximum internal energy – all calculation models (scenarios)

<table>
<thead>
<tr>
<th>Reference model</th>
<th>Maximum Internal energy</th>
<th>[MJ]</th>
<th>165</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed variation</td>
<td>V [m]</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Maximum Internal energy</td>
<td>[MJ]</td>
<td>12.2</td>
<td>-43.2</td>
</tr>
<tr>
<td>Draft variation</td>
<td>D [m]</td>
<td>7.5</td>
<td>11</td>
</tr>
<tr>
<td>Maximum Internal energy</td>
<td>[MJ]</td>
<td>167.0</td>
<td>168.0</td>
</tr>
<tr>
<td>Impact location</td>
<td>x [kmol] [m]</td>
<td>49.74</td>
<td>19.02</td>
</tr>
<tr>
<td>Maximum Internal energy</td>
<td>[MJ]</td>
<td>102.0</td>
<td>165.0</td>
</tr>
<tr>
<td>Angle variation</td>
<td>θ [Deg]</td>
<td>-45</td>
<td>-30</td>
</tr>
<tr>
<td>Maximum Internal energy</td>
<td>[MJ]</td>
<td>95.2</td>
<td>122.0</td>
</tr>
<tr>
<td>Scaled length/ mass variation</td>
<td>L [m]</td>
<td>100</td>
<td>128</td>
</tr>
<tr>
<td>Maximum Internal energy</td>
<td>[MJ]</td>
<td>111.0</td>
<td>165.0</td>
</tr>
</tbody>
</table>
8. Conclusion

The influence of parameters affecting the collision between a tanker and a ferry are examined by non-linear contact based time-domain simulation. A total of 26 collision scenarios are examined. Each collision scenario generates a large amount of data and due to the limited space available only a summary of the findings is presented. As it can be seen in Table 3 the internal hull failure is reached in the majority of collision scenarios.

The speed and mass of the ferry affects the damage significantly and linearly: as expected, the higher the speed and mass, bigger the damage.

The impact location has again a predictable influence on the resulting damage: collision close to the ship's centre of gravity generates highest damage. The impact more to the bow or aft struck ship side generates momentum which induces rotation of the struck ship, and therefore part of kinetic energy of the striking ship is transformed into kinetic energy of struck ship.

Similar behaviour may be observed in the case of angle variation, where orthogonal collision represents the worst case. As the impact angle changes, the effect are less pronounced. However, it should be noted that this might be significantly different if struck ship speed is included in the calculation.

Finally, the variation of the draft shows the complexity of the problem as the internal energy varies in an unpredictable manner. This is so because by changing the draft of the struck ship the geometry that is affected by impact is completely different. For example, if tanker is in ballast, ferry bow might be below the main deck of a tanker. Since main deck alone can absorb the large amount of energy, if it remains unchanged, bigger damage will occur in the affected struck ship structure. On the positive side, breaching the inner hull of an empty tanker will at least dramatically reduce the problem of environment pollution. However, ship integrity may be in danger due to additional damage.

It is safe to say that orthogonal collision represents the worst scenario in any collision. But, if a risk of the marine accident is to be considered, not only the worst cases should be taken into account. This paper addresses the distribution of damage in relation to every collision parameter concerned. This may be then used as input in the collision risk analysis, along with the maritime traffic data, to recognize the high risk zones in the Adriatic in a rational way.

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References