Environmental protection using structural analysis of ships

M Savin¹, A Presura² and I Chirica¹

¹Dunarea de Jos University of Galati, Faculty of Engineering, Domneasca Street, No. 47, 800008, Galati, Romania
²Dunarea de Jos University of Galati, Faculty of Naval Architecture, Stiintei Street, No. 2, 800146, Galati, Romania
corresponding author: adrian.presura@ugal.ro

Abstract. Naval accidents are one of the most common causes of water and coast around pollution and also for the deterioration of the associated ecosystems. In order to reduce the risk of spills of hazardous substances in water one of the methods is to study the behavior of naval structures in the event of collisions.

This paper aims to propose a methodology for collision analyze, the case study being a river barge structure with side impact generated by another barge. The structural analysis used the finite element method with an explicit solver and the dynamic load of the side impact collision was applied in form of initial kinetic energy of the striking ship. Standard ship design Rules are compared with an original approach to reveal the advantages and disadvantages of each method.

The influence of variation of the different parameters on the obtained results is analyzed, in order to outline an efficient and as accurate as possible methodology, considering the necessary computational effort.

1. Introduction

In recent years increased attention has been paid to the urgent need to protect the environment more effectively and also to the safety of ships in case of naval accidents.

At present in the shipbuilding industry have been developed efficient tools to design the ship structures with a good response in the field of elastic deformation, related to local loads and hull girder strength. The methods used for such analysis are well known and well regulated by means of various international organizations and societies in ship construction domain.

Due to increasingly stringent ship safety requirements in case of collision, the idea of analyzing the ship structures in different collision scenarios has been rapidly developed. This new topic of modern engineering, study of the behaviour of various structures in the field of plastic deformations such as body impact, explosion, etc. [1, 2], has seen a strong development also due to tremendous growth of computing technology [3].

By far the most common solution to increase the impact strength of naval structures is the use of double hull, namely double bottom for grounding protection and double side for side collisions.

Using of double hull structure has two justifications:
- ensuring the spaces for other than cargo, like ballast and store tanks, i.e. fuel oil, lube oil, fresh water, sewage etc.
- complying with some specific requirement in case of damage, whether it is protecting tanks with dangerous goods, or whether it is the ship’s safety at collision
IMO, IACS and other authorities in ship construction field have adopted rules regarding the compulsory of double hull structures and also the constructive measures.

Some examples of Rules that establish the double hull requirements, are:
- MARPOL – double bottom and double side for oil pollution prevention,
- SOLAS – double bottom for damage stability,
- MSC.235(52) – double side for pollution prevention,
- IBG, IGC, AND [4] and NMA 123/1994 – double bottom and double side for pollution prevention.

Constructive measures imposed to double hull consists in general in a series of rules for scantling and arrangement of structure, and usually is not required a direct analyze for collisions. This kind of rules takes into account indirectly the behavior of structures to collisions and does not present an explicit approach for an impact situation.

An accurate method to study the ship structure behavior at collision is done by direct analyze with finite element method, used to demonstrated the efficiency of a some structure in case of defined impact scenarios imposed by specific rules (ADN, NMA 123/1994).

The aspects of finite element method used for such analysis are regulated by ship classification societies Rules and by other authorities, the concrete aspects referring to being:
- net thickness,
- model extending,
- structure meshing in finite elements,
- boundary conditions application,
- loading application,
- stress calculations,
- material idealization,
- failure criterion.

To evaluate the level of accuracy of such finite element methods for ship impact analysis there is a series of papers in the literature that compares the experimental results with numerical simulation ones, the conclusion being that a good precision is obtained with proper adjusting of calculation parameters.

However the ship behavior to impact analyzes come with a consistent disadvantage: the high effort put for good precision results. It is true that in last years the computing power of the latest generations of computers has considerably reduced the computing time, but still exist the great effort of preprocessing, related to FEM model generation, and significant influence in results for various parameters used in calculations.

This paper aims to propose a methodology for collision analysis, being investigated the influence of variation of the different parameters on the obtained results, in order to outline an efficient and accurate methodology, having in mind also the necessary computational effort.

2. Case study description
In order to make a comparative analysis between different aspects of impact numerical simulation of a double hull ship was selected as case study an inland navigation barge.

Further are presented the structure of the barge, rule requirements and hypothesis regarding impact calculation and evaluation criteria used to assess the structure strength at collision.

2.1. Description of case study
For structure analysis in the event of side collision the river barge considered has the following characteristics:

| Characteristic     | Value     |
|--------------------|-----------|
| Length overall     | 76.20 m   |
| Breadth            | 11.00 m   |
| Depth              | 3.60 m    |
| Scantling draught  | 3.00 m    |
Frame space: 562 mm

The river barge is open type with single cargo hold, designed to transport bulk cargo and also other types of non homogenous cargoes that can be loaded inside the barge hold.

The ship structure is made in a transverse system of stiffeners, having a double side with 1.0 m width and a double bottom with 0.5 m height. In Figure 1 is illustrated an overview of the structure, showing the ordinary stiffeners in transverse system.

![Figure 1. 3D view of structure section](image)

The main structural elements have the following net thickness:
- bottom: 8 mm
- double bottom: 9 mm
- side & deck: 7 mm
- double side: 6.5 mm
- bottom webs: 5 mm
- side and double side stiffeners: 75x50x5 mm
- cargo hold frame: 9 mm

2.2. Rule Requirements and Hypothesis for numerical analysis

Finite element calculations of ship structures to side impact are done according AND 2017 rules requirements.

- All structural elements have to be modeled with net thickness, in consequence the strength and rigidity will be reproduced accordingly.
- The model extension on longitudinal and transverse way has to take into account that the results from the analyzed area are not influenced by the boundary conditions. In the case of the center line symmetry the structure model can be done only on half of the ship.
- Mechanical characteristics of the material used for the structure are according to steel S235, from Det Norske Veritas RP-C208 [5]:
  - Young’s modulus, \( E = 2.1 \times 10^5 \) MPa,
  - Yield stress \( R_Y = 236.2 \) MPa,
  - Tangent modulus 1105 Mpa,
  - Poisson’s ratio 0.3.
- Additionally, the ultimate criteria according to strain \( \varepsilon_k = 0.171 \), was used.
- This criterion is obtained from [6], with following expression:
where
\[ \varepsilon_k = \varepsilon_g + \varepsilon_e \cdot \frac{l}{l_e} \]  \hspace{1cm} (1)

\[ \varepsilon_g = 0.08 \]
\[ \varepsilon_e = 0.65 \]
\[ t = 7 \text{ mm} \] is the average thickness of the elements
\[ l_e = 50 \text{ mm} \] is the average length of the elements.

According to BV Rules, 2016 [7] and ADN, 2017 the following boundary conditions have been used:
- all three displacements fixed at fore end of the structure model,
- symmetry conditions in transversal plane,
- symmetry conditions in center line.

The friction between the bow and the side was considered with constant friction coefficient \( \mu = 0.3 \). The friction coefficient has been estimated according to European Agreement concerning the International Carriage of Dangerous goods by Inland Waterways:

\[ \mu = \mu_s + (FS - FD) e^{-DC \cdot v_{rel}} \]  \hspace{1cm} (2)

\[ FD = 0.1 \]
\[ FS = 0.3 \]
\[ DC = 0.01 \]
\( v_{rel} \) is relative friction speed.

The dynamic loading of the model was made by considering an initial kinetic energy to the bow model defined through:
- initial speed of 4 m/s on transverse direction - Oy direction,
- bow model weight of 750 t, equivalent to an barge of total 1500 tons displacement.

The ship bow indenter is the bow of a classical inland ship, suggested by ADN, 2017, which is considered as a rigid, having the relative positions illustrated in Figure 2.

\[ T=3.2m \]
\[ T=2m \]

Figure 2. Relative position of striking ship to struck ship

2.3. Evaluation criteria

The following criteria have been taken into account for double hull structure analysis:
- the behavior until end of the impact, with two values: total internal energy and the length of total penetration,
- the behavior until the collapse of the cargo space longitudinal bulkhead, with two values: internal energy and the length of penetration.
3. Finite element analysis of barge side collision

The main goal of finite element calculations presented in this paper is to propose a direct method for collision analysis, using an explicit solver specific for dynamic phenomena like ship side impact, method that will lead to accurate results with reduced computational effort.

One of the aspects that have a major influence on duration of analysis is represented by the size of the model taken into consideration for finite element analysis, so called “model extension”. In the following are presented different model extensions for the river barge case study and finally a comparison is made to evaluate the influence on results accuracy and computational time.

For numerical analysis with plastic deformation and dynamic loads ANSYS – Explicit Dynamics solver has been used [8].

According ADN requirements the criterion for assessing the strength of ship structures at side impact is given by the energy absorbed by the structure until the cargo hold break, the moment when the dangerous products are discharged into the water.

The total computational time of numerical simulation was considered until the initial kinetic energy of striking ship was completely absorbed by the struck ship structure.

The FEM calculations were done using a computing machine with the following configuration:
- 2 processors with 12 cores in total,
- 96 GB RAM memory,
- storage media: 2 x SSD used in RAID 0 (striping) mode.

3.1. Complete barge model with two symmetry conditions

The first analysis was performed on complete model of barge structure, more precisely the longitudinal extension starts from aft end of the barge to mid ship section where the striking ship acted, as can be seen in the Figure 3 below. Two symmetry conditions were used in order to reduce the computational time:
- struck barge center line symmetry,
- striking bow center line symmetry.

![Figure 3. Complete model extension](imageblink)

Boundary conditions used at calculation are the two symmetry conditions described above and additional at aft end of the barge were blocked vertical displacements.

At the end of numerical simulation, virtual time 1.043 seconds, the global deformation of struck structure shows as illustrated in Figure 4 below. It can be observed large deformations of entire barge side structure with failure of cargo hold longitudinal bulkhead, meaning that dangerous cargo inside barge can spill and pollute the environment.
It is observed from Figure 5 that bow model kinetic energy from the start of the simulation, $E_c = (m \cdot v^2)/2 = 6$ MJ, is transferred to the barge structure in two phases:
- first phase, in time interval $0 \to 0.6$ s, with high gradient of energy decreasing
- second phase, in interval $0.6 \to 1.043$ s, with a smaller energy decrease gradient, when practical is consumed only approximate $25\%$ from total energy.

From Figure 6 can be observed also two phases of bow model described by a higher deceleration on first stage and a lower deceleration on the final. Total bow penetration is $2460$ mm from initial position.

3.2. **Limited model with two symmetry conditions**

The second analysis was performed on a limited model of barge structure, in this case longitudinal extension starts at $6.75$ meters from mid ship section where the striking ship acted, as can be seen in the Figure 7 below. Two symmetry conditions were used in order to reduce the computational time:
- struck barge center line symmetry,
- striking bow center line symmetry.
Boundary conditions used at calculation are the two symmetry conditions described above and additional at the free end of the model, opposite side of the section where the striking ship acted, were blocked vertical displacements.

At the end of numerical simulation, virtual time 1.109 seconds, the global deformation of struck structure shows as illustrated in Figure 8 below. In this case also can be observed the failure of cargo hold longitudinal bulkhead with dangerous cargo spill.

It is observed from Figure 9 the same deceleration of the bow model in two phases similar with calculation presented in 3.1.

From Figure 10 can be observed the total bow penetration of 2914 mm from initial position.
3.3. Limited model with one symmetry condition

The third analysis was performed on a limited model of barge structure, in this case longitudinal extension starts at 6.75 meters from mid ship section where the striking ship acted, as can be seen in the Figure 11 below. In contrast to the model presented in 3.2, this time the structure was modeled completely, from one side to the other, and only one symmetry condition was used in order to compare the computational time and obtained results with the limited model with two symmetry conditions presented above:

- striking bow center line symmetry

![Figure 11. Limited model extension without center line symmetry](image1)

Boundary conditions used at calculation are the symmetry condition described above, additional at the free end of the model, opposite side of the section where the striking ship acted, were blocked vertical displacements and the transversal displacement (Oy direction) of the side shell were blocked in the opposite board of the ship than being hit.

At the end of numerical simulation, virtual time 1.124 seconds, the global deformation of struck structure shows as illustrated in Figure 12 below. In this case also can be observed the failure of cargo hold longitudinal bulkhead with dangerous cargo spill.

![Figure 12. Limited model deformation, with one symmetry: transversal (left) and longitudinal (right)](image2)

It is observed from Figure 13 the same deceleration of the bow model in two phases similar with calculation presented in 3.1. From Figure 14 can be observed the total bow penetration of 2907 mm from initial position, very close value to results from 3.2 calculation.
Figure 13. Kinetic energy at limited model one symmetry conditions

Figure 14. Displacement of limited model one symmetry conditions

4. Conclusions
The summary of the three analysis results are centralized in the table below:

| Table 1. Summary of results |
|-----------------------------|
|                           | 3.1          | 3.2          | 3.3          |
| Results                    | Complete model | Limited model two symmetry | Limited model one symmetry |
| Total                      | Internal energy | 5.075 MJ | 4.134 MJ | 4.412 MJ |
|                           | Bow penetration | 2460 mm | 2914 mm | 2907 mm |
| Until failure              | Time of failure | 0.654 s | 0.376 s | 0.368 s |
|                           | Internal energy | 4.276 MJ | 1.153 MJ | 1.207 MJ |
|                           | Bow penetration | 2119 mm | 1434 mm | 1405 mm |
| Total                      | Computation time | 170.5 hours | 25.7 hours | 46.3 hours |

By comparing the above results two main conclusions can be drawn:
- symmetry condition from center line should be used, since the analysis results are very close (see results from 3.2 and 3.3) and computational time is drastically reduced by over 44 %,
- a limited model of the ship is a more conservative way to evaluate the strength of the structure subject to impact, because for a limited model the structure will fail earlier and the energy absorbed will be less that in real situation. In other words if the main goal is to design a structure with an increased reserve of impact strength it is desirable to use an limited model for numerical simulation and on the other side if the designer aims to create an lighter structure that it has to calculate more precisely the impact internal energy so will have to use an complete model.

Is worth noting also that the complete model total computational time is much higher than limited models, 660% compared with model in 3.2, so if limited computation resources are available then a smaller model will be the solution, but considering the fact that in this way the analysis will be more conservative.

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