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Grounding crashworthiness of an inland floating structure

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Abstract. Considering the morphological and hydrological phenomena that occur within the inland navigation waterways and the constant maintenance required to ensure safe navigation limits, the risk of grounding of ships can be considered imminent at any given moment. The latter, combined with the year-round fluctuations in the water depth, increases furthermore the risk of accidents. The purpose of the current paper is to evaluate the crashworthiness of a typical inland structure under different grounding scenarios. The study numerically analyses the grounding effect on a river-barge structure. To calibrate the numerical model, a benchmark collision study has been reproduced and the obtained results have been compared. Based on the previous studies of the Danube riverbed, the shape of the indenter has been chosen and employed within the framework of this paper. The analysis study has been performed considering the structure without preload, as well as the ballast and full loading pre-stressed conditions, for a transversal angle of attack of the indenter. Following the grounding impact analysis sets, the damage of the subjected structure has been evaluated using the maximum displacement of the indenter and the total internal deformation energy consumed.

1. Context

The modifications of the riverbed geometry within the inland navigation waterways represent a constant challenge for the administration, ship-owners and nonetheless the shipbuilding industry. For the issues at hand, different and cost-effective calls must be made. In this direction, from an engineering perspective, the current paper analyses the impact of multiple grounding scenarios on the most common inland floating structure, the river barge.

In 2017, in a bathymetric and morphological study of a Danube sector published by Nicolae et al., key geometrical descriptions of the riverbed have been presented and are significant in the framework of constructing different grounding analyses scenarios[1]. Figure 1 presents the analyzed Danube sector, which is located at km 346 on the inland navigable waterway from Sulina.

Figure 1. Location of Bala branch (N 44.1906, E27.5689, Google Maps)[1][2]

For safe navigation conditions, the Danube Commission recommends a minimum depth of 2.5 m and a width between 150 – 180 m, all year round [3]. Currently, according to the water depths reports of the AFDJ Administration, the sounding depth at Danube km 345 is around 4.7 m at centre, and the waterway width is around 180 m.

From the riverbed cross-sections extracted through bathymetric procedures, a typical simplified form of an indenter can be generated (Fig. 2) [1]. Further, the truncated cone shape, described in Figure 2 has been idealised (Fig. 3) and the geometry used in the grounding impact analysis.

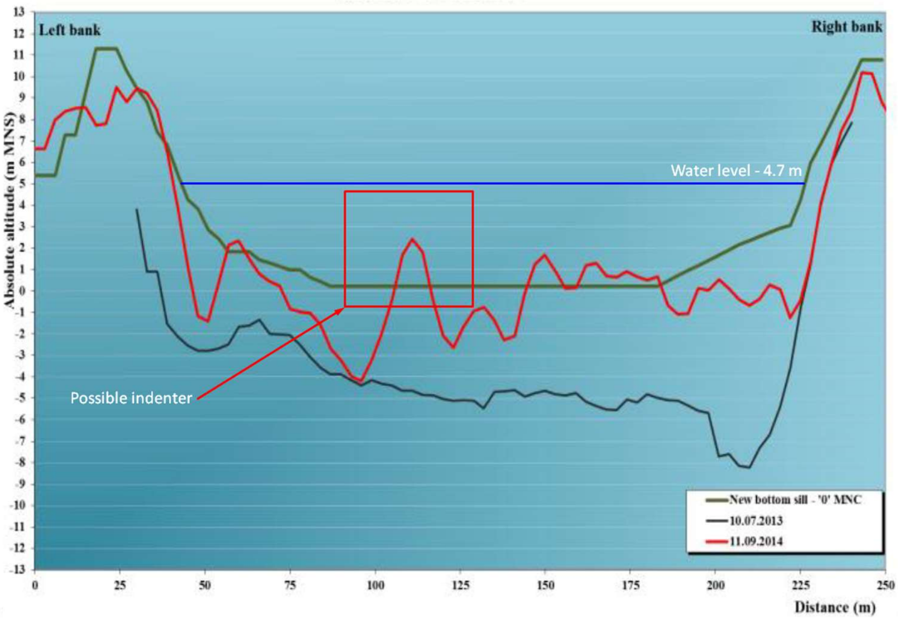

Figure 2. Danube riverbed cross-section in 2013-2014, designed bottom sill [1]

1.1 Structural and material model

The geometry of the structure consists of a midship section from a 3000 DWT barge having the main dimensions described in Table 1. The midship section of the analysed model is extended over 14 meters in length and half breadth in width (Fig. 3), containing all the main structural elements.

Table 1. Barge main particulars

Length overall	L_{OA}(m)	90
Breadth	B(m)	11
Depth	D(m)	4.5
Draught, Ballast	D_b(m)	0.565
Draught	T(m)	3.8
Displacement, Lightship	(t)	507.5
Displacement, Ballast	(t)	529.5
Displacement, Full load	(t)	3620.8
Ballast, no trim condition	(t)	22
Deadweight	(t)	3113.3

The structural arrangement of the barge, as well as the idealised indenter, are presented in Figure 3. Simplifications have been considered for the generation of the CAD model using equivalent L profiles replacing the typical holland profiles (HP) used in the shipbuilding industry, conserving the mechanical properties of the latter.

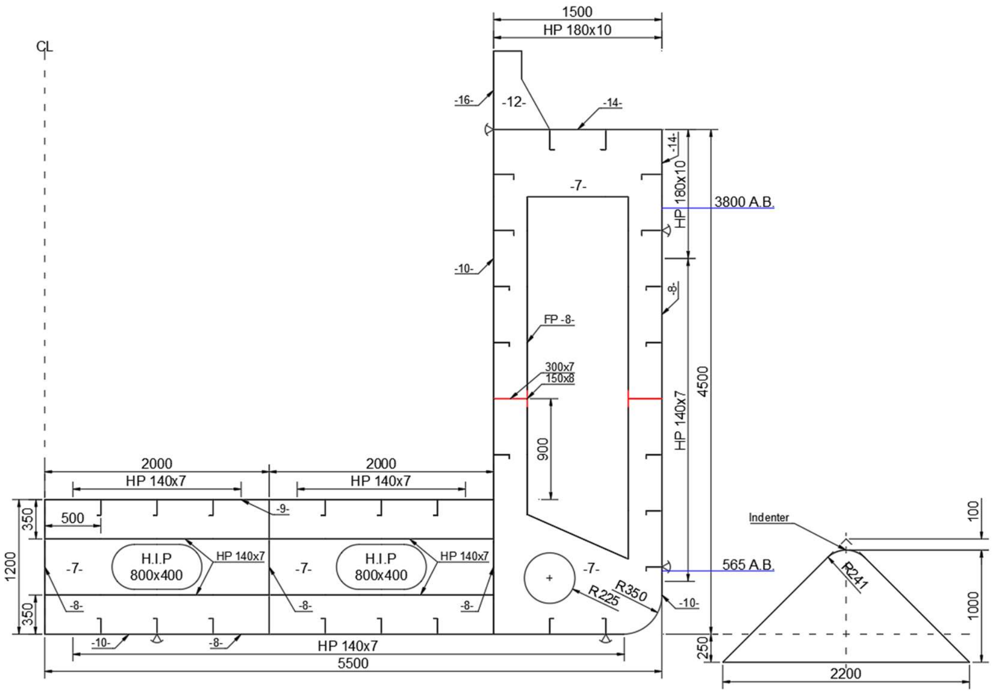

Figure 3. Standard web frame and idealised indenter geometry [4][5]

The nonlinear plastic material model used in the numerical analysis is described by a bilinear stress-strain curve (Fig.4), in agreement with ADN rules, that has the yielding stress of 235 MPa and ultimate strength of 400 MPa [6][7].

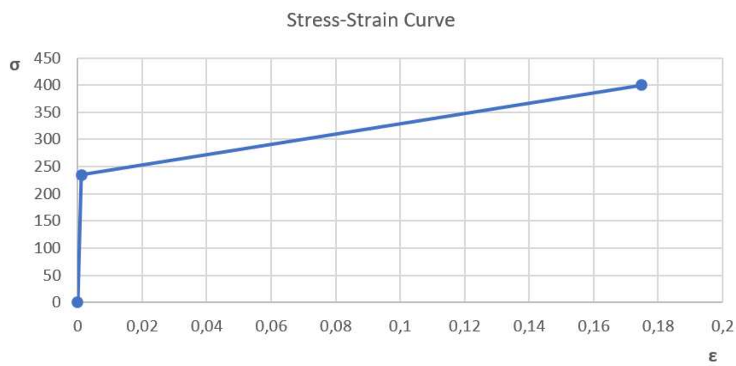

Figure 4. Stress-Strain curve [7]

1.2. Analysis setup

For the present study, two grounding scenarios have been considered. The first approach consists of the basic impact analysis which considers the structural model without the state of tensions and deformations. For the approach, the hydrostatic pressures and cargo loads are considered. The preloaded state of the structure has been achieved by running the static analysis first, from which the displacement at nodes has been extracted and integrated into the dynamic explicit input solver file. To avoid domain integration schemas and the possibility of information translation errors, the same mesh size distribution across the CAD model has been considered for both static and dynamic analyses.

The structural model described in Figure 3 has been subjected to grounding impact loads considering the idealised indenter position and geometry, based on the context and simplifications previously discussed. The initial conditions are represented by an imposed velocity of 1389 mm/s on the indenter's geometry, corresponding to the speed of a barge navigating upstream. The indenter's mass (Table 1) varies for the ballast and full loading grounding scenarios, for a discrete representation of the inertial characteristics of the barge.

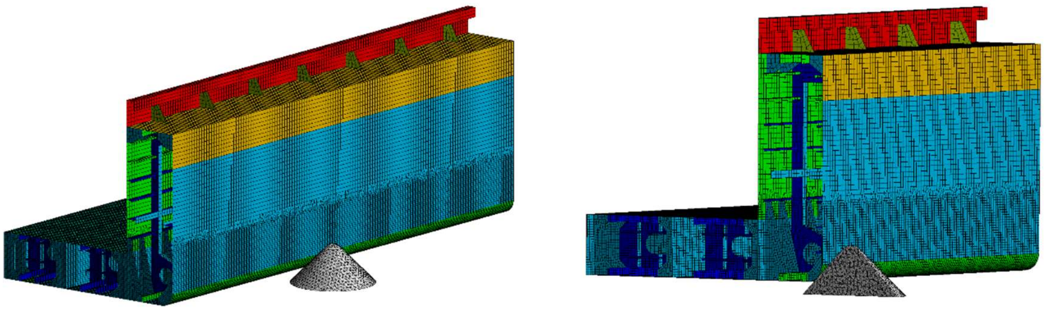

Figure 5. Structural mesh. Complete model (left), section through indenters centre line (right)[8]

The boundary conditions applied on the mesh are represented by the symmetry condition at the centre line, and continuity of the structure at the fore and aft model limits, for a minimum influence over the results.

2. Numerical validation of the procedure

To evaluate the results obtained, a benchmark analysis project has been reproduced [9][10]. The geometry of the structure subjected to impact in the analysed benchmark contains a structural arrangement that resembles a typical hull bottom of a ship.

The chosen benchmark study uses the geometry of the analysed structure described by Ringsberg et al. (2018) (Fig. 6)[9]. Following the same assumptions and modelling techniques as the study at hand, the constitutive finite element model was generated. The FEA model uses 4 cornered shell elements and 5 integration points on the shell thickness. The indenter displaces with a constant velocity of 5 m/s for a total simulation time of 0.1 s. The simulation time in relation to the distance that the indenter displaces ensures the full penetration of the structure.

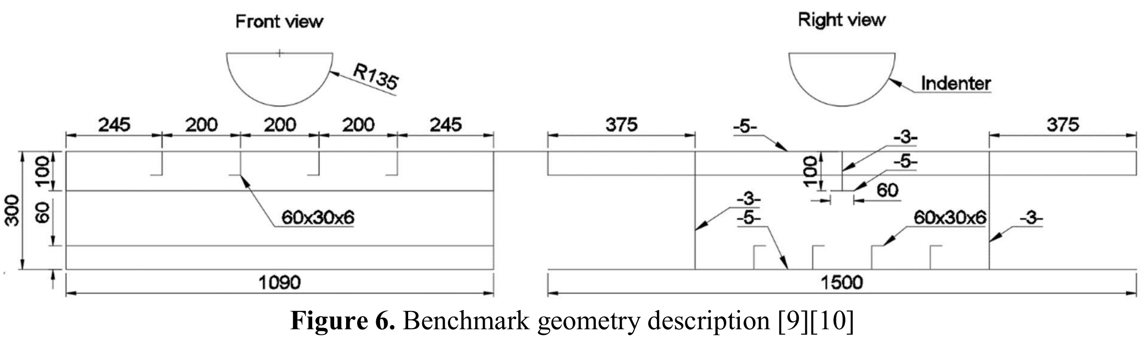

Figure 6. Benchmark geometry description [9][10]

The results have been compared by means of the variation of the total force in relation to the displacement of the indenter. Figure 7 presents the correlation between the author's result set (FEA-2022) and the benchmark study (Test – experimental, FEA).

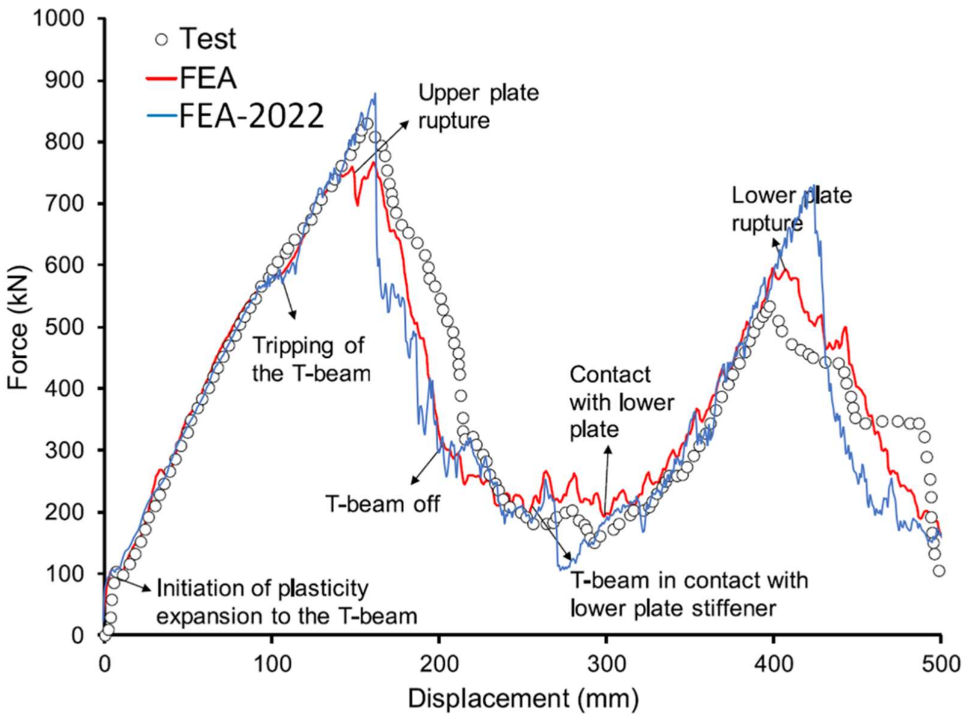

Figure 7. Force-displacement response compared with the benchmark [9][10]

From the force-displacement plot comparison between the results obtained within the current framework and the benchmark analysis, as well as the experimental data available, it can be observed that, with few differences, the general trends of the maximum forces registered are respected. The most important disjunctions appear for the structural relief part after the upper plate rupture and for the total necessary force to penetrate the lower plate. The obtained results are considered by the authors of enough precision to evaluate the structural integrity and crashworthiness of the proposed study. General data regarding the states of deformations and maximum stresses occurring after the reproduction of the benchmark will not be presented since the current study does not treat the qualitative aspects of the analysis, but the quantitative general view that can be of use within the industry, considering the applicability of the available scientific general knowledge for the matters at hand.

3. Results and discussions

In the following section, the results of the grounding impact analysis are discussed considering both cases of structural impact, with and without preloading from the static analyses.

Figure 8 shows the difference between maximum von Mises stresses occurring in the impacted area for the ballast loading condition. It is visible from the stress contour plot of the interest area that the distribution of the von Mises stresses moves from the area of the double bottom to the side shell area. Maximum values of remanent von Mises stresses are registered, as expected for preloaded case A2, with a maximum of 395.7 MPa.

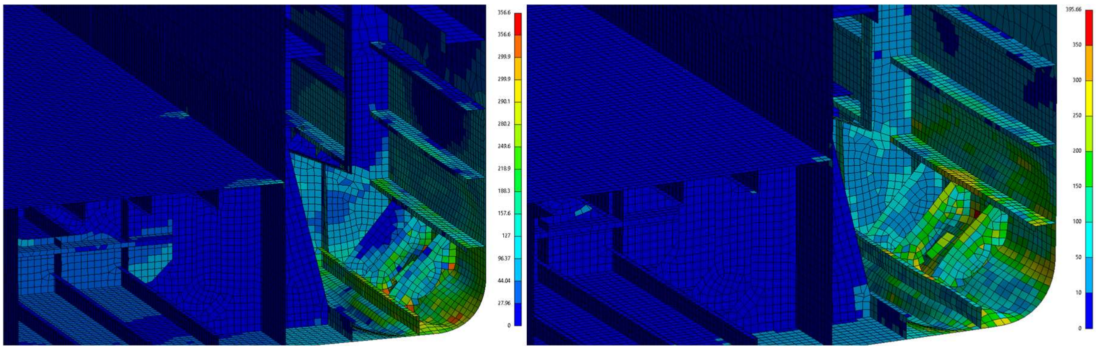

Figure 8. von Mises stresses, Case A1-Ballast-No preload (left), Case A2-Ballast-Preloaded (right)

The total deformations for analysed cases A1 and A2 are presented in Figure 9. The maximum deformations occur for the structure not loaded. Local, out of plane plastic deformations with material failure are identified.

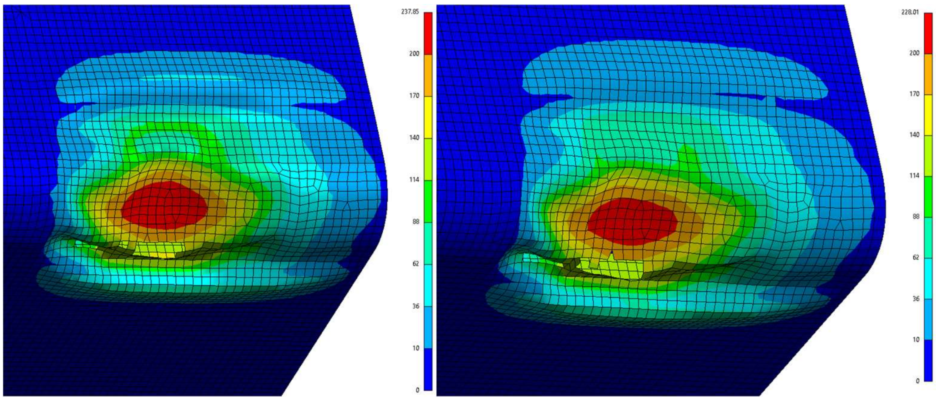

Figure 9. Total deformation, Case A1-Ballast-No preload (left), Case A2-Ballast-Preloaded (right)

Figure 10 presents the von Mises stresses for the structure subjected to grounding impact loads having the mass of the indenter equal to the full load displacement of the barge. For this case, plastic deformations are not localised only in the directly impacted area of the outer shell and stiffening members but are also transmitted to the plates of the cargo holds. It is to be kept in mind that the effect of the cargo pressure on the inner shell is present. The maximum equivalent stresses in this area, as well as the stress distribution, can be observed to have different values. Having the structure preloaded with hydrostatic pressure on the outer shell and in the cargo hold reduces the effects of the grounding impact loads on the latter, but at the same time, it can be observed and increase in the damage of the stiffening members of the bottom structure.

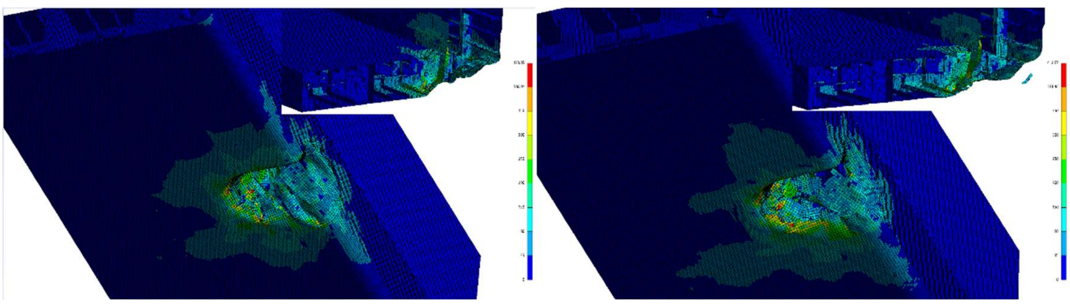

Figure 10. von Mises stresses, Case A3-Full Load-No preload (left), Case A4-Full Load-Preloaded (right)

Maximum calculated deflections registered for the structure preloaded are approximate 1146 mm and are presented in Figure 11 (right). Even if the distance travelled by the indenter in this analysis case is the same for both simple and preloaded model, it can be observed that the major differences are at the level of structural failure modes.

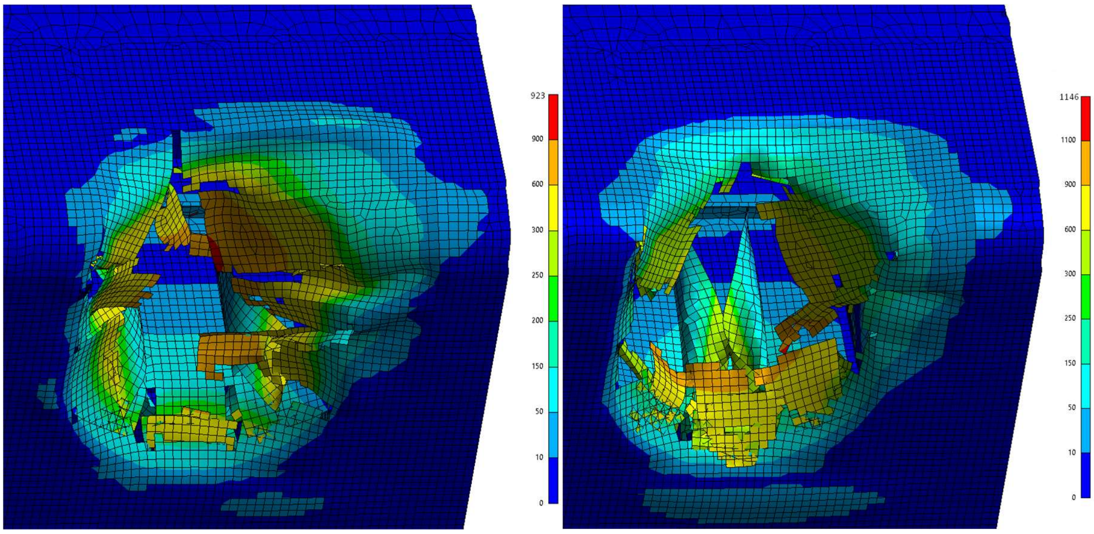

Figure 11. Total deformation, Case A3-Full Load-No preload (left), Case A4-Full Load-Preloaded (right)

Table 3 summarises the numerical results obtained following the numerical analysis. The damage of the outer shell has been observed in all analysed cases. The preloading of the model, as expected, modifies the behaviour of the structure, and it is more quantifiable larger for the full loading scenario. The internal energy consumed for the preloaded case at full loading condition registers increased differences of approximately 18 % with respect to the structure not loaded.

Table 2. Grounding analysis results

Analysis case		A1	A2	A3	A4
Indenter mass		Ballast	Ballast	Full load	Full load
Structural state		No preload	Preloaded	No preload	Preloaded
Direction		90º	90º	90º	90º
Eq. stress vM	[MPa]	356.6	395.7	423.9	412.9
Eq. plastic strain	[mm/mm]	0.308	0.283	0.300	0.268
Normal stress - X	[MPa]	-277.9	-257.7	446.8	383.3
Normal stress - Y	[MPa]	-264.9	284.9	303.4	338.1
Normal stress - Z	[MPa]	-264.9	284.9	-367.2	357.1
Shear stress - XY	[MPa]	-147.7	-136.5	188.4	-192.9
Shear stress - YZ	[MPa]	-142.3	-204.7	179.9	184.4
Shear stress - XZ	[MPa]	-120.0	-176.8	-161.8	192.8
Max. kinetic energy	[MJ]	0.489	0.489	3.482	3.482
Internal energy	[MJ]	0.352	0.355	1.40	1.7096
Shell penetration	-	YES	YES	YES	YES
Indenter displ.	[mm]	340.2	340.1	1848.7	1848.8
Total deformation	[mm]	238	228	923	1146

4. Conclusions

The numerical evaluation of impact loads on a ship's hull should be carefully treated. The approaches should be always verified with a benchmark study or by implementing a small comprehensive experiment for the validation of the numerical method. The preload of an impacted structure brings new insights into the failure modes of the structural elements. Deflections present in a structural model, even from a quasi-static analysis perspective, can alter the behaviour of the structure, and therefore the results obtained.

Further analysis will contain the ultimate strength evaluation of the damaged structure after the grounding scenario.

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