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STRUCTURAL EVALUATION OF AN INLAND BARGE STRUCTURE UNDER FORE AREA GROUNDING IMPACT LOADS

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Abstract: The inland shipping industry has a long history of utilizing barges for transportation purposes. However, due to their design and navigation conditions, barges are susceptible to impact damage when navigating through inland waterways. In this study, the authors investigated the effects of a grounding impact on the fore area of a barge structure. The analysed finite element model has been developed with a high structural fidelity representation of a typical inland navigation barge of 3000 DWT. The specific fore area of the barge was subjected to a range of grounding impact scenarios, and the response was analysed using 3D FEM simulations. The results of the study include external force, total internal deformation energy, maximum recorded von Mises stress, and stress triaxiality factor. This study provides valuable insights into the behaviour of barges subjected to foregrounding impact scenarios. The results of the study are intended to be used by shipbuilding structural designers to develop safer and more robust barge hulls that are less susceptible to impact damage. Furthermore, the results of the study can also be used to inform regulations and guidelines for the maritime industry, to improve the safety and reliability of barge transportation.

Key words: Inland vessel, barge, finite element method, fore area grounding, impact analysis.

1. INTRODUCTION

Inland barges have been utilized for transportation purposes for decades due to their cost-effective and environmentally friendly nature. However, they are susceptible to damage from grounding incidents when navigating through inland waterways, which can lead to significant economic and environmental consequences.

The grounding incidents of inland barges are a significant problem in the shipping industry. Despite their slow speed, barges are vulnerable to grounding due to their design, which makes them susceptible to impact damage when navigating through shallow waters with uneven beds. Grounding incidents can cause significant damage to the barge structure, and cargo, leading to environmental hazards. Several studies investigated the effects of grounding incidents on inland barges. Sha et al. [1] conducted a numerical analysis of the fore area of an inland navigation barge subjected to a range of grounding impact scenarios, providing insights into the behaviour of barges under such conditions. Amdahl et al. [2] investigated the response of a barge hull subjected to a grounding impact using experimental methods, focusing on the development of a robust hull design. Similarly, Dørum et al. [3] conducted experiments to study the effects of grounding incidents on the structural behaviour of inland barges. Yu [4] proposed a new numerical model for analysing the grounding impact on the hull of inland barges, taking into account the effects of non-linear soil resistance. Makouei et al. [5] analysed the effects of grounding incidents on the structural integrity of barge hulls, using finite element methods, while Teixeira et al. [6] developed a probabilistic model for assessing the risk of grounding incidents on inland barges. Other studies have also explored the topic of grounding incidents on inland barges. Bhatia and Mehra [7] conducted a study on the effect of water depth and barge speed on the impact force during grounding. Chauhan et al. [8] carried out a numerical investigation of the impact of different types of barges on the scour around bridge piers. Aziz et al. [9] investigated the impact of grounding incidents on the stability of barge loads during transportation. Kumar et al. [10] studied the effects of grounding incidents on the bending moments and shear forces of barge hulls. Chen et al. [11] analysed the impact of grounding on the stability of barge loads during the transportation of bulk cargoes.

In this study, the authors used the Ansys workbench [12] to perform the explicit finite element analysis, considering element failure to investigate the effects of grounding incidents on the fore area of a typical inland navigation barge [13]. The analysed 3D FEM finite element model represents the fore area of a 3000 deadweight tonnes barge, having a length of 90 m, full loading draught of 3.8 m, with a total displacement of 3620.8 t (Table 1).

Table 1. Main characteristics, 3000 dwt inland navigation barge.		
Length overall	L_{OA}(m)	90
Breadth	B(m)	11
Height	H(m)	4.5
Draught	T(m)	3.8
Displacement, Lightship	Δ_{light}(t)	507.5
Displacement, Ballast	$\Delta_{ballast}$(t)	529.5
Displacement, Full load	Δ_{full}(t)	3620.8
Ballast, no trim condition	$M_{ballast}$(t)	22

Table 1 outlines the main characteristics of the inland navigation barge used in this study, including its length overall, breadth, depth, draught, displacement in lightship, ballast, and full load conditions, as well as the ballast in a no-trim condition. The analysis has been performed only for the full loading condition.

The current paper provides valuable insights into the behaviour of barges subjected to grounding forward impact scenarios. The results include external force, total internal deformation energy, maximum recorded von Mises stress, and the stress triaxiality factor [14]. The presented results can be used by shipbuilding structural designers to develop safer and more robust barge hulls and to inform regulations and guidelines for the shipping industry, to improve the safety and reliability of barge inland transportation [15].

2. GEOMETRY, FEA MODEL DESCRIPTION AND STUDY METHODOLOGY

The present study aimed to investigate the structural response of an inland navigation barge under different grounding scenarios. A surface 3D-CAD model for the bow area of the barge was generated using the Ansys built-in modeller Space Claim (Fig.1). The mesh consisting of approximately 200000 elements and nodes was created based on the surface geometry (Figs. 2, 3) [16, 17]. The steel grade A material formulation is provided by the international inland shipping rules (ADN) [18], which has a yield stress limit of 235 MPa and rupture stress limit of around 400 MPa. In Ansys Explicit solver, the plastic deformations and the eventuality of element rupture failure are employed by the EOSDEF (Equation of state definition) function. The EOSDEF is based on various parameters such as stress, strain or energy [12]. The study considered four grounding scenarios and includes relevant navigation setup: two heading angles (0 and 45 degrees) into the reference of the riverbed notch, with two forward speeds (8 and 15 km/h).

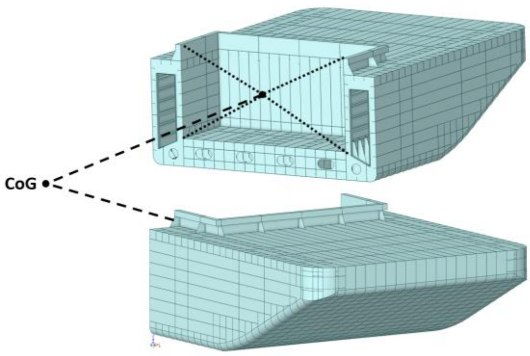

Fig. 1. 3D-CAD Geometry and boundary condition assumption. [12, 17]

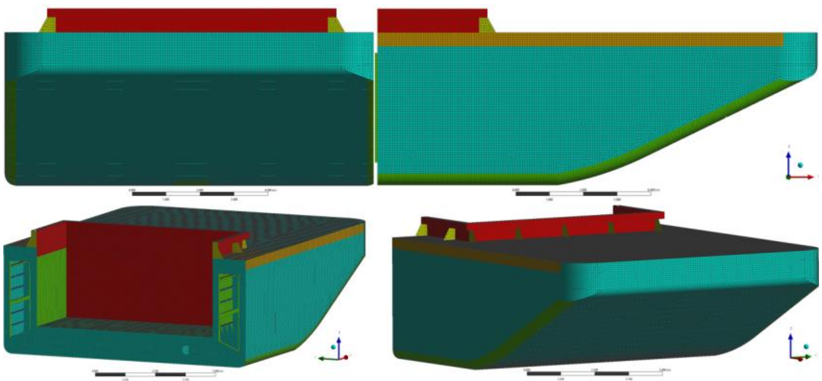

Fig.2. 3D-FEM model of 3000 dwt inland navigation barge [12, 17]

Boundary conditions are applied at the location of the center of gravity (CoG) of the fully loaded barge (Fig.1), taking into account specific displacement and rotational constraints, connected by rigid 1D elements to the fore structure [16]. The impacted surface in each scenario was described as a typical Danube River bank, which has been considered to be rigid.

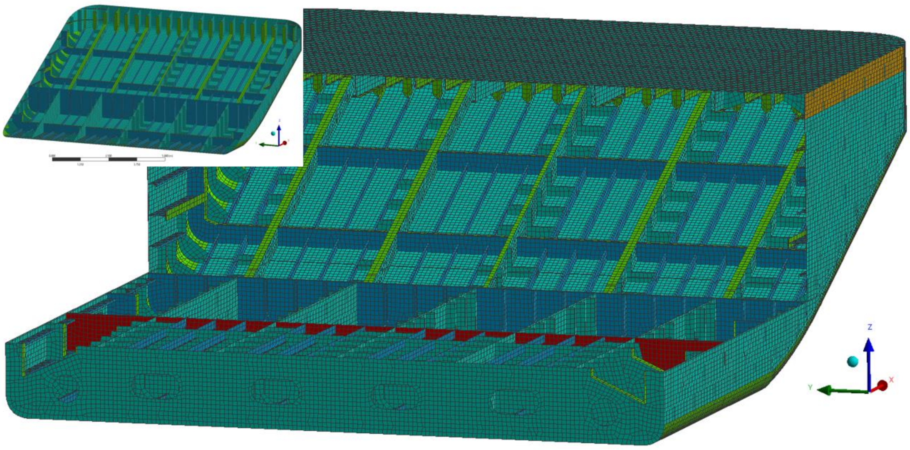

Fig. 3. 3D-FEM model structural arrangement details [12, 17]

3. RESULTS AND DISCUSSIONS

In the following section, the numerical results obtained are presented and discussed. Table 2 summarizes the maximum values of calculated kinetic energy for the two different heading angles and velocities of the inland navigation barge, the von Mises stresses, equivalent plastic strain, total internal deformation energy and the status of element failure, following the numerical analysis for all four cases analysed.

Table 2. Results summary

Description	U.M.	Case 1	Case 2	Case 3	Case 4
Heading	[degrees]	0	0	45	45
Speed	[km/h]	8	15	8	15
Equivalent Stresses - von Mises	[MPa]	320.43	329.77	315.23	325.33
Equivalent Plastic Strain	[m/m]	0.176	0.173	0.177	0.179
Kinetic energy	[MJ]	8.934	31.422	8.934	31.422
Internal deformation energy	[MJ]	0.625	0.692	0.137	0.184
Element failure	YES/NO	NO	NO	NO	NO

In the cases analysed, the internal deformation energy of the barge is considerably less than its kinetic energy, because the impact with the ground leads to a relatively small amount of plastic deformation. This suggests that the barge can withstand the grounding loads without sustaining significant damage, and no large deformations, which is a desirable outcome in terms of safety and cost-effectiveness. The above effects are due to the specific geometry of the grounded riverbed, as well as the geometry of the barge's bow. For the analysed cases, the bow geometry, which has an angle of approximately 30 degrees, leads to a sliding phenomenon more than a direct impact, involving more crushing of the structure and element deformation due to excessive strain.

Figures 4 and 5 present the stress triaxiality factor distribution across the analysed bow barge structure for the heading angle of $\mu=0^{o}$, and speeds of v=8 km/h and v=15 km/h. The result figures show the stress triaxiality with the highest value of 0.222 and the lowest value of negative -0.221, -0.222. These values suggest that the stress state in the material is predominantly compressive, with the highest value indicating a higher level of compression compared to the lowest value. In other words, the hydrostatic stress (the pressure component of the stress state) is high relative to the equivalent (von Mises) stress, which takes into account both the pressure and shear components of the stress state. This type of stress state is typically associated with ductile materials, which can deform and neck down before breaking. A high-stress triaxiality can cause plastic deformation, which can result in permanent deformation or yielding of the material, but it may not necessarily cause failure due to fracture.

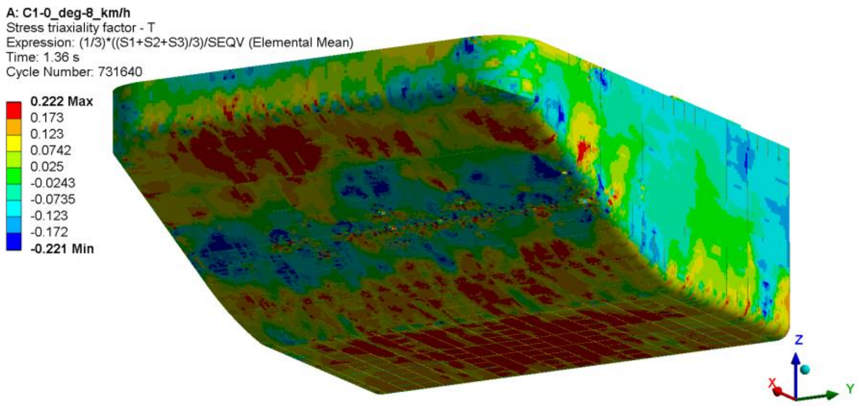

Fig. 4. Stress triaxiality factor distribution, Case 1, μ=0º, v=8 km/h

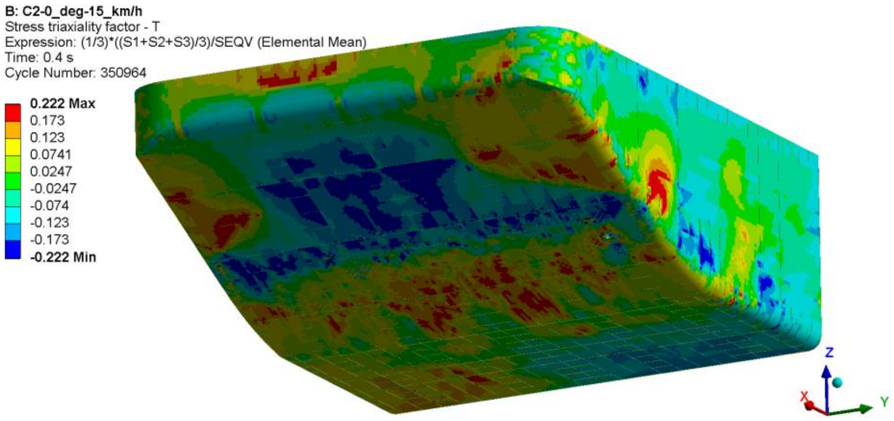

Fig. 5. Stress triaxiality factor distribution, Case 2, μ=0º, v=15 km/h

Figures 6 and 7 present the variation of the vertical external force and the internal energy over time calculated in the numerical analysis. It can be observed that the natural consequence of the physical phenomena following the grounding scenario is being simulated in the form of force surges propagating through the structural model. The maximum value of the acting force has been calculated for the initial contact with the riverbed, with a further reduction of approximately half of the initial and decreasing over time. From the analysis of the two below graphical representations of the vertical external force and the internal energy (Fig.6), which stabilizes over time, it can be concluded that the finite element system describing the structural model of the barge will not experience further plastic deformations or element rupture failure.

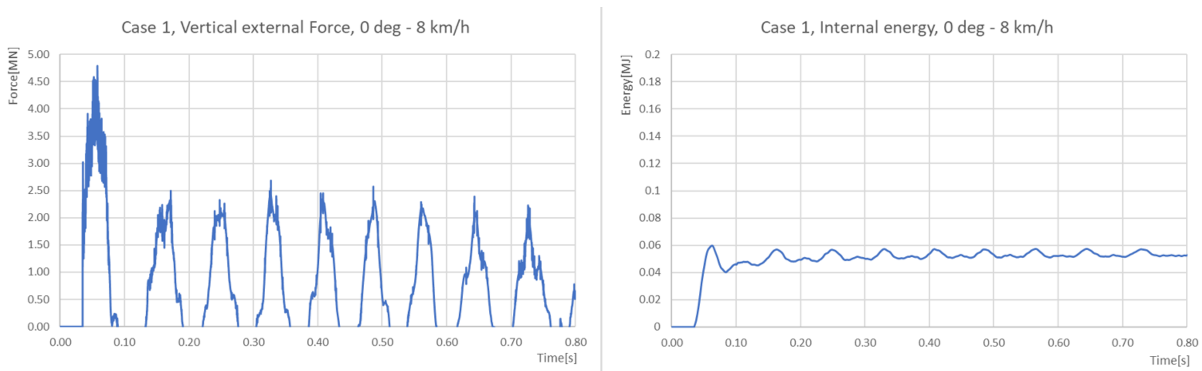

Fig. 6. Vertical external force (left), Internal energy (right), Case 1, μ=0º, v=8 km/h

Figure 7 follows the same trendline as the above Figure 6, differences can be pointed out due to the increase in speed to 15 km/h, in the form of higher peak values for the vertical external force. The width of the vertical external force for the impact at 15 km/h is approximately double in comparison with the 8 km/h impact in the first analysed case, due to the bow sliding on the riverbed notch. From the internal energy evaluation standpoint, the analysis presents two plateaus for the energy absorbed within the structural model, one corresponding to the initial impact, and further following the second impact which increased the internal deformation energy with the approximate value of 0.04 MJ. Since the internal energy values remain within the same range, it can be concluded that plastic deformations occurred in the structural model.

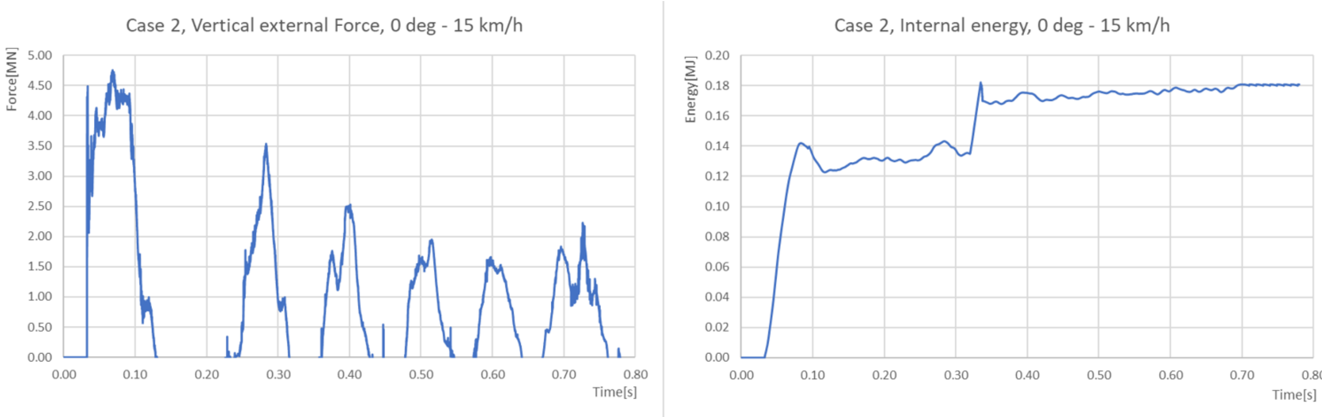

Fig. 7. Vertical external force (left), Internal energy (right), Case 2, μ=0°, v=15 km/h

Figures 8 and 9 present the stress triaxiality factor distribution across the analysed bow barge structure for the heading angle of μ=45°, and speeds of v=8 km/h and v=15 km/h. For the oblique heading angle of the barge in reference to the riverbed notch, it can be noticed that the effects of the grounding have a smaller influence on the impacted zone and the surrounding structure. A stress triaxiality factor of 0.222 and -0.222 indicates a state of stress where the hydrostatic stress component is significantly higher than the deviatoric stress component.
In general, a stress triaxiality factor of less than 1 indicates a state of stress that is more likely to result in ductile failure, while a stress triaxiality factor of greater than 1 indicates a state of stress that is more likely to result in brittle failure. However, the exact threshold value for ductile versus brittle failure can depend on the material being tested and the loading conditions. The stress triaxiality factor distribution maps major differences for the two different speeds analysed in the current study. The presence of positive and negative high-concentration areas for stress triaxiality can have different implications depending on the specific context and characteristics of the material or structure being analysed. However, these regions can be potential sites for material failure or damage, as they may experience higher levels of stress or deformation than other areas. Therefore, it is important to carefully evaluate and monitor these regions to ensure the safety and integrity of the structure.

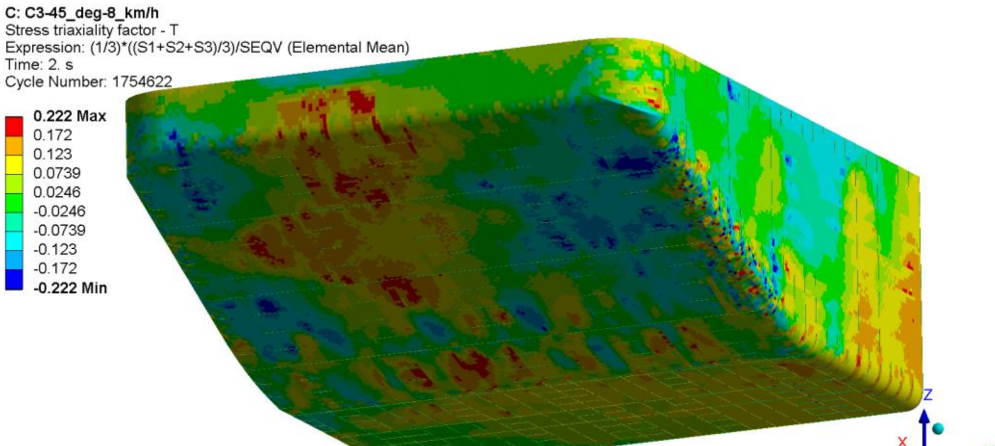

Fig. 8. Stress triaxiality factor distribution, Case 3, μ=45°, v=8 km/h

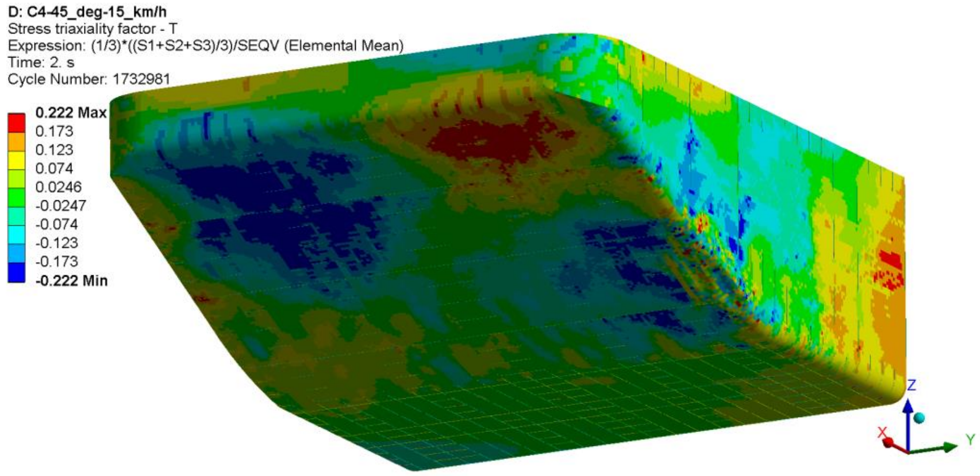

Fig. 9. Stress triaxiality factor, Case 4, μ=45°, v=15 km/h

Figures 10 and 11 present the vertical external force (left) and the internal energy (right) for cases 3 and 4, heading angle of μ=45°, and speeds of v=8 km/h and v=15 km/h. The high values of the forces acting on the structure do not exceed 2 MN. In grounding impact analysis of the barge's bow area, the angle of impact relative to the heading direction appears to have less influence on the structural response compared to direct μ=0° impacts. However, the total amount of energy absorbed by the structure in the form of plastic deformation is significantly different between the cases 3 and 4, when the barge is travelling at a speed of 15 km/h compared to 8 km/h. Another particularity of the oblique grounding impact scenario is represented by a single peak in maximum vertical external force, followed by a constant lower value over time, while the bow lateral area slides across the riverbed. Even though the maximum values of the internal deformation energy are in the same range for both heading angles, μ=0° (cases 1 and 2) and μ=45° (cases 3 and 4) respectively, the total area affected by plastic deformation is smaller for the latter cases.

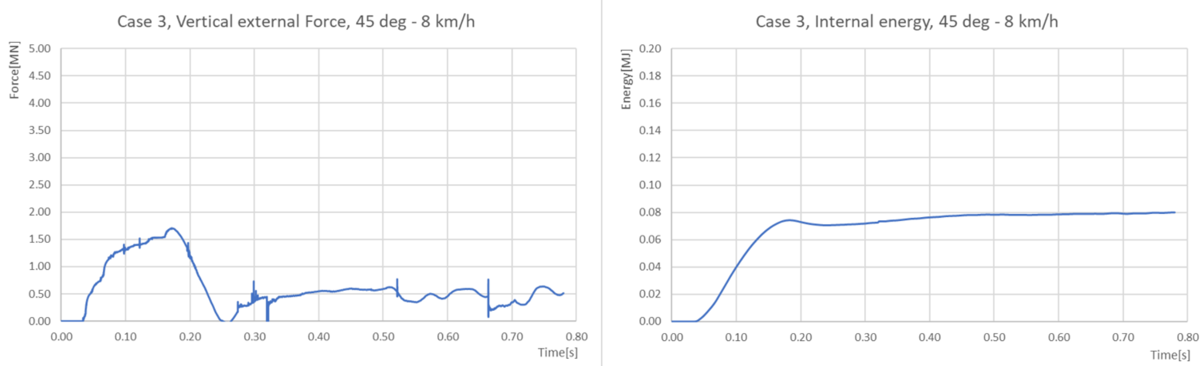

Fig. 10. Vertical external force (left), Internal energy (right), Case 3, μ=45°, v=8 km/h

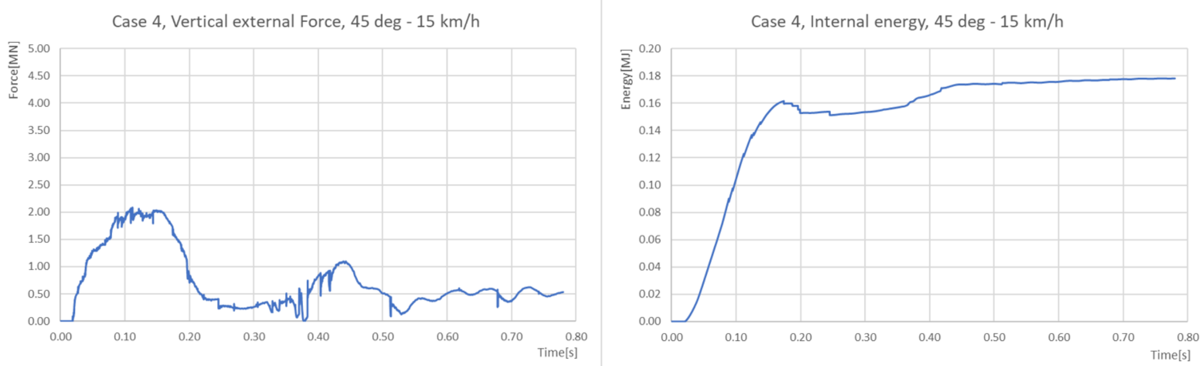

Fig. 11. Vertical external force (left), Internal energy (right), Case 4, μ=45°, v=15 km/h

4. CONCLUSIONS

In this study, the effects of a grounding impact on the fore area of a barge structure were investigated using Ansys Workbench Explicit Dynamics 3D FEM simulation [12]. The results show that the barge can withstand the grounding loads without sustaining significant damage or large deformations. The internal deformation energy of the barge was considerably less than its kinetic energy, suggesting a desirable outcome in terms of safety, in major part due to the bow shape. The stress triaxiality factor distribution showed that the stress state in the material was predominantly compressive, which is typically associated with ductile materials that can deform and neck down before breaking. It is to be pointed out that for all the analysed cases, no element rupture failure has been registered, with maximum von Mises stresses calculated situated in the plastic deformation region. The maximum value of the acting force was calculated for the initial contact with the riverbed notch, with a further reduction of approximately half of the initial and decreasing over the analysed time.

The stress triaxiality factor [14] is an important parameter that provides information about the deformation and failure mechanisms of materials under high strain rate loading conditions. In an impact analysis, stress triaxiality can be used to predict the type of failure mode that is likely to occur. A very high value of stress triaxiality, particularly in combination with high levels of equivalent stress, can cause the material to fail through a combination of ductile and brittle failure mechanisms. In such cases, the high compressive stresses can cause the material to deform and neck down, while the high shear stresses can cause localized cracks and fractures to form, leading to structural failure.

Understanding stress triaxiality is crucial in designing structures and components that are subjected to impact loading, as it helps engineers and analysts to better understand the failure behaviour of materials under such loading conditions. The results presented in this paper can be used to optimize the design of ship structures and components subjected to impact loading, to ensure that they can withstand high strain rate loading conditions without experiencing structural and material failure.

Further investigations on the bow grounding impact analysis concerning inland navigation barges will be performed considering the effects of multiple barge convoys as well as the different geometries and the behaviour under similar accidental loading conditions.

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