

VIII International Conference “In-service Damage of Materials: Diagnostics and Prediction” (DMDP 2025)

Mechanical behavior assessment of dynamic ice forces using FE method: Interaction with an idealized offshore structure

Paskah Ridho Tumanggor^{a,b}, Aprianur Fajri^a, Aditya Rio Prabowo^{a,*}, Sören Ehlers^{c,d},
Moritz Braun^c, Quang Thang Do^e, Haris Nubli^f, Hermes Carvalho^{g,h}

^a Department of Mechanical Engineering, Universitas Sebelas Maret (UNS), Surakarta, Indonesia

^b Laboratory of Design and Computational Mechanics, Faculty of Engineering, Universitas Sebelas Maret (UNS), Surakarta, Indonesia

^c Institute for Maritime Energy Systems, German Aerospace Center (DLR), Geesthacht, Germany

^d Institute for Ship Structural Design and Analysis, Hamburg University of Technology (TUHH), Hamburg, Germany

^e Department of Naval Architecture and Ocean Engineering, Nha Trang University, Nha Trang, Vietnam

^f School of Engineering, University of Surrey, Guildford, United Kingdom

^g Department of Structural Engineering, Federal University of Minas Gerais, Belo Horizonte, Brazil

^h Department of Structural Engineering and Geotechnical, University of São Paulo, São Paulo, Brazil

Abstract

Dynamic interaction between sea ice and offshore structures is a critical factor in design for operations in cold regions. This study investigates ice impact through numerical simulation to provide information relevant to offshore structural design. A finite element model was developed to simulate the collision between an ice sheet and a conical structure, with ice velocity as the primary parameter. The calculations were carried out using an explicit dynamics approach, which enables the simulation of time-varying impact forces. The results indicate that higher ice velocities result in greater stress within the ice sheet, generating larger reaction forces on the structure, with the increase following a nonlinear trend. These findings provide quantitative insight into the magnitude of loads that may be transmitted to offshore structures, underscoring the importance of accounting for dynamic ice forces in structural design.

© 2026 The Authors. Copy from the contract: Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of DMDP 2025 organizers

Keywords: Sea ice; offshore structures; finite element analysis; explicit dynamics; ice impact

1. Introduction

The expansion of offshore activities into cold-region environments has increased the demand for reliable design methods that account for dynamic ice-structure interaction. Sea ice impacts are transient events characterized by high strain-rate deformation, nonlinear contact forces, and localized stress concentrations that can cause cracking and damage to structural components (Kondratenko and Tarovik, 2020; Mintu and Molyneux, 2022; Hammer et al., 2023). The structural response to such impacts is strongly governed by the ice impact velocity, which directly controls the kinetic energy transferred to the system. Even small changes in velocity can lead to significant variations in internal stress and reaction forces, influencing the overall safety and

* Corresponding author. Tel.: +62-271-163-632; fax: +62-271-163-632.

E-mail address: aditya@ft.uns.ac.id

performance of offshore installations (Xiu *et al.*, 2022; Yakimov *et al.*, 2023; Sinsabvarodom *et al.*, 2024). Conical structures, such as ice-breaking cones, have been widely adopted in cold region engineering because their sloping geometry can transform vertical impact loads into lateral components, thereby reducing the transmitted force and promoting bending or shear failure of the ice (Bergström *et al.*, 2016; Wang *et al.*, 2022; Song *et al.*, 2023). This geometry allows part of the vertical load to be redirected horizontally, resulting in lower peak forces than with vertical members. However, as the impact velocity increases, the interaction between the ice sheet and the structure becomes more dynamic, producing larger radial and circumferential stresses near the contact zone. Understanding the mechanical behavior of ice sheets under various impact velocities is therefore crucial for predicting load magnitudes and evaluating the structural performance of offshore systems in ice-prone regions (Ehlers and Østby, 2012; Hartmann *et al.*, 2022; Suryanto *et al.*, 2023).

Recent advances in numerical modeling have enabled detailed investigation of these complex interactions. The finite element method (FEM) has become one of the most powerful tools for simulating ice deformation and stress distribution during impact events (Liu *et al.*, 2023; Tuhkuri and Polojärvi, 2018). The explicit dynamic formulation, in particular, is suitable for short-duration collision problems as it allows direct time integration and accurate representation of nonlinear contact and deformation behavior (Hammer *et al.*, 2023; Prabowo *et al.*, 2016; 2018; 2023). Furthermore, probabilistic and hybrid numerical approaches have improved the prediction of ice load variability as a function of impact velocity, ice geometry, and mechanical strength (Sinsabvarodom *et al.*, 2024).

Accordingly, this study presents a three-dimensional numerical investigation of the mechanical response of a level ice sheet impacting an idealized conical offshore structure under varying impact velocities. Simulations were performed using an explicit dynamic finite element approach to ensure accurate representation of transient impact behavior. A consistent modeling framework was maintained across all velocity cases to provide a uniform basis for evaluating the impact of speed on stress distribution. The outcomes of this study are expected to advance offshore structural design in ice-prone regions by providing quantitative insight into the evolution of radial and circumferential stresses, thereby improving understanding of the dynamic ice-loading mechanism on sloped structures.

2. Numerical Method and Model Description

A three-dimensional finite element (FE) model was developed to simulate the dynamic impact between a level ice sheet and a conical offshore structure resting on a rigid foundation. The model configuration, including the relative positions of the ice sheet, cone, and supporting water domain, is illustrated in Figs. 1(a) and 1(b), which present the top and bottom views of the system, respectively.

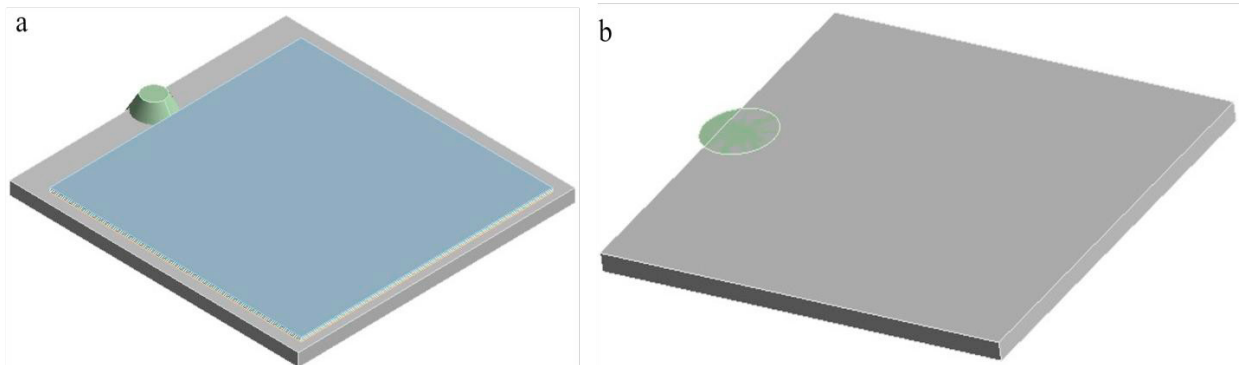


Fig. 1. Model configuration: (a) top view; (b) bottom view.

This configuration provides a simplified yet representative framework for analyzing the stress response and load transmission during ice–structure interaction. The ice sheet, measuring $20\text{ m} \times 20\text{ m} \times 0.3\text{ m}$, was positioned horizontally above the cone to represent an idealized level-ice condition. The conical structure was designed with a base radius of 2 m, a top radius of 0.835 m, and a cone angle of 60 degrees, representing the geometry typically used in ice-resistant offshore platforms.

The material properties employed in the simulation are summarized in Table 1. The density and elastic constants were selected based on representative values reported in the literature for ice and structural steel used in cold-region applications. These properties provide a physically consistent basis for evaluating stress propagation and deformation during collision events. The ice sheet was modeled as an isotropic, linearly elastic solid to capture its deformation response under impact loading, whereas the conical structure was treated as a rigid body. In this model, water was not represented as a physical fluid; instead, it was idealized as a rigid body serving as a numerical support for the ice sheet (Blackerby and Wu, 2006). This assumption was adopted to eliminate hydrodynamic effects and fluid–structure interactions, thereby isolating the ice–cone interaction mechanism of interest. By assigning a very high stiffness to the water body and fully constraining it, deformation beneath the ice sheet was effectively

suppressed. As a result, stress development and bending behavior occurred predominantly within the ice. Consequently, the role of water in this model was limited to providing geometric support and contact boundary conditions, rather than representing realistic fluid behavior. In addition, this idealization strategy reduced computational cost while allowing the analysis to focus on stress evolution within the ice sheet.

Table 1. Mechanical properties of materials (Blackerby and Wu, 2006).

Model Component	Density (kg/m ³)	Young's Modulus (Pa)	Poisson's Ratio
Ice sheet	960	1E9	0.27
Cone	7850	2E11	0.3
Idealized rigid base	1006	2E11	0.3

The mesh configuration adopted in the model is shown in Fig. 2. The ice sheet was discretized using hexahedral elements with a $100 \times 100 \times 3$ division, ensuring a uniform element distribution along its length, width, and thickness. The conical structure was modeled using shell elements to reduce computational cost while maintaining sufficient accuracy in representing the contact interface. A gravitational acceleration of 9.8 m/s^2 was applied in the negative Z -direction in all simulations to represent realistic environmental conditions.

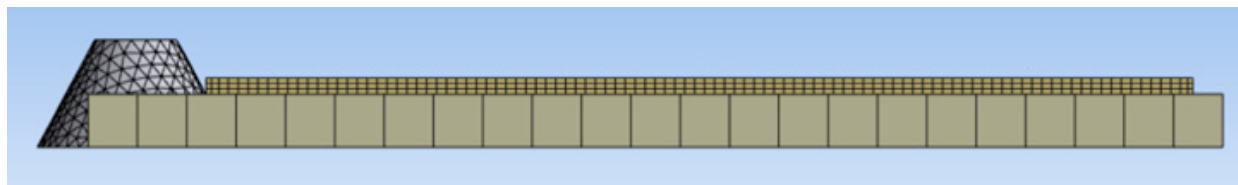


Fig. 2. Finite element mesh details.

The conical structure and the water foundation were fully constrained in all translational and rotational degrees of freedom to prevent rigid-body motion during impact. In contrast, the ice sheet was allowed to move and deform freely in accordance with the contact definition between the ice and the cone. These boundary conditions were defined to ensure an accurate physical representation of the system. Contact interactions were governed by a surface-to-surface contact algorithm with penalty enforcement, enabling the capture of contact pressure and frictional effects at the interface. This configuration ensured stable contact convergence and realistic load transfer during the impact process (Ridwan et al., 2023; Malsyage et al., 2025)

3. Results and Discussion

The numerical simulations effectively captured the dynamic response of the ice structure system during impact loading. The explicit dynamic approach provided accurate temporal resolution of stress propagation and deformation within the ice sheet. During the initial contact phase, a rapid rise in stress occurred near the cone tip as the impact force was transmitted into the ice, followed by a redistribution of stresses through both radial and tangential components. This response illustrates the characteristic transient behavior of ice under dynamic loading, where stress localization and strain-rate effects dominate the mechanical response.

The results indicate that the conical geometry plays a crucial role in governing the stress distribution within the ice. The inclined surface of the cone transforms a portion of the vertical impact load into lateral components, thereby influencing how the ice deforms and how the reaction forces develop at the interface. The subsequent contour plots of circumferential and radial stresses provide insight into these mechanisms and how the structure's geometry contributes to stress redistribution during the impact event.

3.1. Stress distribution analysis

The stress distribution generated within the ice sheet during impact was analyzed through circumferential and radial stress contours at varying impact velocities, as presented in Figs. 3 and 4, respectively. These contour plots provide a comparative visualization of how internal stresses evolve with increasing impact speed during the ice–structure interaction.

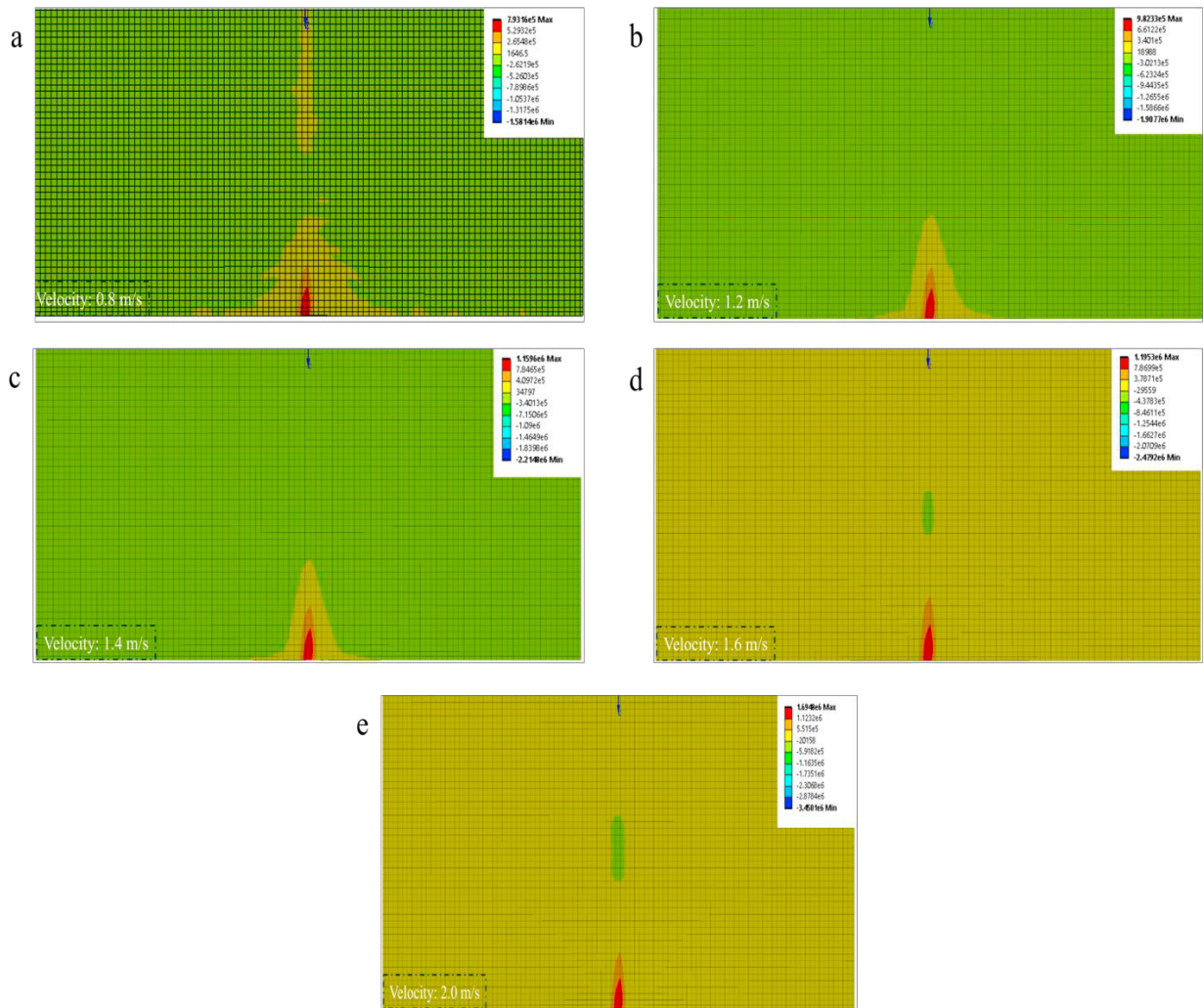


Fig. 3. Circumferential stress contour distributions of the ice sheet under varying impact velocities: (a) 0.8 m/s; (b) 1.2 m/s; (c) 1.4 m/s; (d) 1.6 m/s; (e) 2.0 m/s.

In Fig. 3, the circumferential stress contour exhibits a distinct and continuous band of tangential stresses surrounding the contact interface between the ice and the cone. The pattern forms an elliptical ring wrapping around the conical surface, with the highest stress concentration located near the midsection of the slope. The contour lines are densely packed in this region, reflecting the intense shear interaction occurring along the cone's inclined surface. Away from the contact zone, the contour color gradually fades, forming a smooth gradient that indicates the redistribution of tangential loads along the ice surface. The orientation of the stress field follows a curved, nearly circular trajectory consistent with the cone geometry. At the same time, a mild asymmetry appears on one side of the pattern, likely caused by localized differences in surface curvature or contact stiffness. This continuous band of tangential stress shows how the shear component of the load propagates laterally around the cone's perimeter, a typical circumferential stress response during ice-structure interaction (Sodhi, 2001; Timco and Frederking, 1990).

In Fig. 4, the radial stress contours show a compact, circular zone of high compressive stress directly beneath the cone tip, indicating the primary impact region. The stress distribution radiates outward symmetrically from this point, forming a concentric pattern that decreases gradually in intensity with distance. The inner area of the contour appears sharply defined, suggesting strong compressive localization, while the outer rings become progressively smoother, indicating dissipation of the impact load through the ice thickness. Stress propagation follows the vertical axis of the cone, with the stress vectors predominantly oriented along the direction of impact. The contour lines form evenly spaced gradients that trace the transmission of compressive energy from the central zone toward the surrounding areas. The overall configuration highlights the axial symmetry of radial stress distribution, with compressive forces directed downward and outward in a concentric pattern through the ice body.

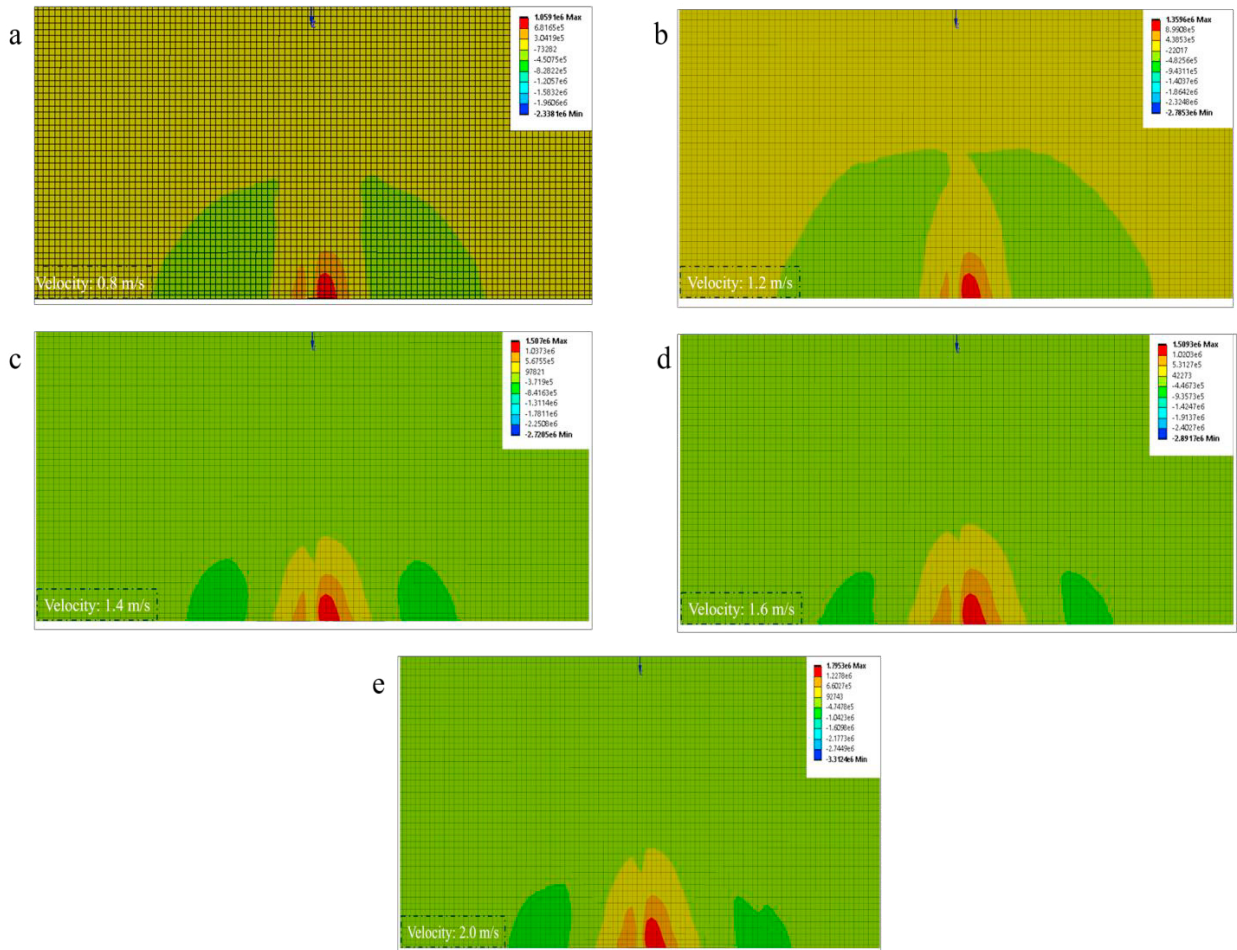


Fig. 4. Radial stress contour distributions of the ice sheet under varying impact velocities: (a) 0.8 m/s; (b) 1.2 m/s; (c) 1.4 m/s; (d) 1.6 m/s; (e) 2.0 m/s.

3.2. Effect of impact velocity on stress response

The influence of impact velocity on the internal stress response of the ice sheet was examined by evaluating numerical results for loading conditions ranging from 0.4 to 2.0 m/s. This analysis aims to identify how variations in dynamic loading intensity affect the stress evolution within the ice during contact with the conical structure. The simulation outcomes were assessed by extracting the peak circumferential and radial stresses for each case, which are summarized in Table 2. These data provide a quantitative description of how stress magnitudes develop as the kinetic energy of the impacting ice increases.

Table 2. Maximum radial and circumferential stress values at various impact velocities.

Velocity (m/s)	Max. Circumferential Stress (Pa)	Max. Radial Stress (Pa)
0.4	4.0813×10^5	7.8764×10^5
0.6	6.2219×10^5	9.5311×10^5
0.8	7.9316×10^5	1.0591×10^6
1.0	9.3544×10^5	1.2991×10^6
1.2	9.8233×10^5	1.3596×10^6
1.4	1.1596×10^6	1.5070×10^6
1.6	1.1953×10^6	1.5645×10^6
1.8	1.4201×10^6	1.6625×10^6
2.0	1.6948×10^6	1.7953×10^6

Table 2 presents the maximum values of circumferential and radial stresses recorded during the collision process for all simulated velocities. Each stress value corresponds to the maximum intensity observed at the ice–cone interface at any time during the simulation. As indicated in the table, both stress components exhibit a progressive change with increasing impact velocity, reflecting the dynamic interaction between inertia effects and localized deformation. The numerical variations across the velocity range capture the inherent sensitivity of ice material response to changes in impact rate, particularly under short-duration loading conditions representative of ice–structure collisions.

To further visualize these results, the data from Table 2 are represented graphically in Fig. 5, which plots the maximum circumferential and radial stresses as a function of impact velocity. Each set of data points corresponds to the simulation outcomes, while the solid lines represent fitted regression curves for both stress components. The figure effectively illustrates how stress magnitude evolves with increasing velocity, enabling a more precise comparison of the two stress behaviors.

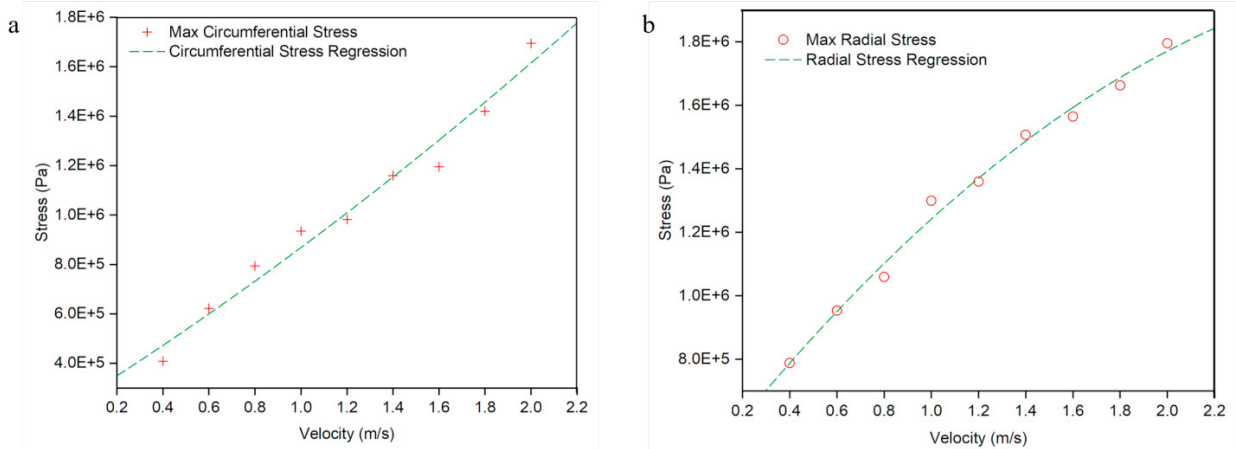


Fig. 5. Relationship between maximum stress and impact velocity for: (a) circumferential stress; (b) radial stress

As shown in Fig. 5, both circumferential and radial stress components display a clear nonlinear correlation with impact velocity. The fitted regression curves indicate that stress magnitudes increase progressively as the kinetic energy imparted by the moving ice sheet becomes greater. This nonlinear relationship demonstrates that the ice–structure interaction is highly strain-rate-dependent, with even modest increases in velocity leading to a significant amplification of internal stress. The simulation results also confirm that the explicit dynamic formulation successfully captures the transient growth of stress intensity during short-duration impact events, producing smooth, continuous regression profiles that indicate stable computational convergence.

In Fig. 5(a), the circumferential stress exhibits a gradual and nearly quadratic increase with respect to velocity. This trend suggests that the tangential stress component is mainly governed by lateral shear deformation generated along the inclined surface of the cone. As the velocity increases, the cone geometry redirects a portion of the vertical impact force into horizontal directions, thereby producing distributed shear stresses around the contact perimeter. The smooth curvature of the regression line implies that the tangential stress field evolves steadily without abrupt fluctuations, indicating a relatively uniform redistribution of strain around the conical surface. Such behavior aligns with the expected mechanical response of ice under shear-dominated loading, where deformation propagates outward rather than concentrating at a single point.

In Fig. 5(b), the radial stress increases more sharply with impact velocity, revealing a stronger nonlinear dependency compared to the circumferential component. The pronounced curvature of the regression line indicates that compressive stresses along the impact axis increase with velocity, reflecting the dominant role of inertia-driven loading in this direction. The localized amplification of radial stress near the cone tip indicates that the ice undergoes intense compression and strain-rate hardening, resulting in a high stress concentration in the central region of contact. This response is consistent with previous experimental findings on dynamic ice impacts, which report that normal stress components tend to increase disproportionately with velocity because ice's limited capacity to dissipate energy through plastic flow limits its ability to accommodate deformation.

Comparison of the two curves in Fig. 5 reveals that the stress evolution within the ice sheet follows two distinct yet interrelated mechanisms. The circumferential stress represents the tangential redistribution of load caused by the sloping geometry of the cone, while the radial stress corresponds to direct compressive transfer along the impact axis. The radial regression curve is relatively steeper than the circumferential one, indicating that compressive loading intensifies more rapidly with velocity, leading to a dominant stress concentration near the cone tip. This contrast highlights the differing deformation responses in the ice sheet: tangential shear spreads laterally, while compressive stress accumulates axially as velocity increases.

4. Conclusions

This study numerically investigated the dynamic interaction between an ice sheet and a conical offshore structure using an explicit dynamic finite-element method. The developed model successfully simulated the transient mechanical response of ice during impact, capturing the evolution of stress and deformation at varying impact velocities. The results showed that stress concentrations primarily occurred at the ice–cone interface, where radial and circumferential stresses exhibited distinct directional distributions. The radial component was aligned with the impact axis, forming a concentrated compressive region beneath the cone tip. Meanwhile, the circumferential stress extended tangentially along the cone surface, creating a continuous stress band around the contact zone.

The analysis further indicated that increasing impact velocity led to a nonlinear rise in both stress components, reflecting the coupled effects of kinetic energy and deformation rate on the ice response. These findings offer quantitative insights into the mechanical behavior of ice under dynamic loading, underscoring the importance of accounting for velocity-dependent ice forces in the design of offshore structures. The established numerical framework serves as a foundation for future research that incorporates additional physical effects, such as ice fracture, temperature dependence, and fluid–structure interaction, to enhance the realism and predictive capability of sea-ice impact simulations.

Acknowledgements

This work was supported by the RKAT PTNBH Universitas Sebelas Maret Year 2025, under the Research Scheme of “Penelitian Kolaborasi Internasional” (KI-UNS), with research grant/contract no. 369/UN27.22/PT.01.03/2025. The authors highly acknowledge this support.

References

- Bergström, M., Erikstad, S. O., Ehlers, S., 2016. Assessment of the applicability of goal- and risk-based design on Arctic sea transport systems. *Ocean Engineering*, 128, 183-198.
- Blackerby, J., Wu, W., 2006. Numerical Simulation of Dynamic Ice Forces on Offshore Structures. Clarkson University NSF REU: Marine Science and Engineering in China. Report, 13p.
- Ehlers, S., Østby, E., 2012. Increased crashworthiness due to arctic conditions – The influence of sub-zero temperature. *Marine Structures*, 28(1), 86-100.
- Hammer, T. C., Willems, T., Hendrikse, H., 2023. Dynamic ice loads for offshore wind support structure design. *Marine Structures*, 87, 103335.
- Hartmann, M. C. N., Onorato, M., Vita, F. D., Clauss, G., Ehlers, S., Polach, F. V. B. U., Schmitz, L., Hoffmann, N., Klein, M., 2022. Hydroelastic potential flow solver suited for nonlinear wave dynamics in ice-covered waters. *Ocean Engineering*, 259, 111756.
- Kondratenko, A. A., Tarovik, O. V., 2020. Analysis of the impact of arctic-related factors on offshore support vessels design and fleet composition performance. *Ocean Engineering*, 203, 107201.
- Liu, R., Xue, Y., Lu, X., 2023. Coupling of Finite Element Method and Peridynamics to Simulate Ship-Ice Interaction. *Journal of Marine Science and Engineering*, 11(3), 481.
- Malsyage, D., Bahatmaka, A., Kirana, A. C. C., Won, L. S., Hee, S. Y., 2025. Finite Element-Based Evaluation of Double-Hull Midsection Performance under Oblique Collision. *Mekanika: Majalah Ilmiah Mekanika*, 24(2), 121-135.
- Mintu, S., Molyneux, D., 2022. Ice accretion for ships and offshore structures. Part 1 - State of the art review. *Ocean Engineering*, 258, 111501.
- Prabowo, A.R., Bae, D.M., Sohn, J.M., Cao, B., 2016. Energy behavior on side structure in event of ship collision subjected to external parameters. *Heliyon*, 2(11), e00192.
- Prabowo, A.R., Muttaqie, T., Sohn, J.M., Bae, D.M., 2018. Nonlinear analysis of inter-island roro under impact: Effects of selected collision's parameters on the crashworthy double-side structures. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 40(5), 248.
- Prabowo, A. R., Ridwan, R., Braun, M., Song, S., Ehlers, S., Firdaus, N., Adiputra, R., 2023. Comparative study of shell element formulations as NLFE parameters to forecast structural crashworthiness. *Curved and Layered Structures*, 10(1), 20220217.
- Ridwan, R., Sudarmo, S., Nubli, H., Chasan, A., Istanto, I., Pratama, P. S., 2023. Numerical Analysis of Openings in Stiffeners under Impact Loading: Investigating Structural Response and Failure Behavior. *Mekanika: Majalah Ilmiah Mekanika*, 22(2), 115-125.
- Sinsabvarodom, C., Leira, B. J., Høyland, K. V., Næss, A., Samardžija, I., Chai, W., Komonjinda, S., Chaichana, C., Xu, S., 2024. On Statistical Features of Ice Loads on Fixed and Floating Offshore Structures. *Journal of Marine Science and Engineering*, 12(8), 1458.
- Song, M., Jiang, Z., Liu, K., Han, Y., Liu, R., 2023. Dynamic response analysis of a monopile-supported offshore wind turbine under the combined effect of sea ice impact and wind load. *Ocean Engineering*, 286, 115587.
- Sodhi, D. S., 2001. Crushing failure during ice-structure interaction. *Engineering Fracture Mechanics*, 68(17–18), 1889–1921.
- Suryanto, S., Prabowo, A. R., Muttaqie, T., Istanto, I., Adiputra, R., Muhayat, N., Fajri, A., Braun, M., Ehlers, S., 2023. Evaluation of high-tensile steel using nonlinear analysis: Experiment-FE materials benchmarking of LNG carrier structures under low-temperature conditions. *Energy Reports*, 9(Supplement 9), 149-161.
- Timco, G. W., Frederking, R. M. W., 1990. Compressive strength of sea ice sheets. *Cold Regions Science and Technology*, 17, 227-240.
- Tuhkuri, J., Polojärvi, A., 2018. A review of discrete element simulation of ice-structure interaction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376, 20170335.
- Wang, G., Zhang, D., Yue, Q., Yu, S., 2022. Study on the dynamic ice load of offshore wind turbines with installed ice-breaking cones in cold regions. *Energies*, 15(9), 3357.
- Xiu, Y., Wang, Q., Li, Z., Li, G., Lu, P., 2022. Estimating spatial distributions of design air temperatures for ships and offshore structures in the Arctic Ocean. *Polar Science*, 34, 100875.
- Yakimov, V., Gaidai, O., Wang, F., Wang, K., 2023. Arctic naval launch and recovery operations, under ice impact interactions. *Applications in Engineering Science*, 15, 100146.