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Educational Simulation of Hull Deflection in Ro-Ro Ferry Vessels: Analyzing Hydrostatic Pressure with Variations in Plate Thickness and Seawater Depth

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Abstract

The construction system is one of the most considered aspects in designing a ship, as the strength of the structure is the most crucial element that ensures the safety of the crew, passengers, and cargo carried. The ship's construction design must be able to withstand various loads or forces, both from inside and outside the ship. The purpose of this study is to determine the deflection of the Ferry Ro-Ro hull due to hydrostatic pressure with variations in plate thickness and seawater depth. This research uses modeling of the Ro-Ro ferry plate deflection due to seawater hydrostatic pressure with the finite difference method. The simulation results show that increasing the plate thickness from 10.0 mm, 15.0 mm, 20.0 mm to 25.0 mm significantly reduces the hull deflection, with the maximum deflection from about 2400 mm decreasing to less than 500 mm. In addition, the water depth also affected the deflection, where an increase in depth from 5 m, 10 m, and 15 m, caused the maximum deflection to increase from about 150 mm to 450 mm. The deflection pattern is parabolic with the maximum deflection occurring at the center of the ship, as the largest hydrostatic pressure distribution is at the center of the ship.

Keywords: educational simulation, finite difference method (FDMs), numerical methods

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INTRODUCTION

A ship is a structure used for transportation at sea and acts as a link between islands. The construction system is one of the most considered aspects in designing a ship, because the strength of the structure is the most crucial element that ensures the safety of the crew, passengers, and cargo carried. The ship construction design must be able to withstand various loads or forces, both from inside and outside the ship (Takami et al., 2019). Hull design is important in shipbuilding because it will affect the condition of the ship in terms of stability, speed, fuel consumption, the depth required in relation to the harbor pool to be visited and the depth of the shipping channel traversed by the ship. The shape of the hull greatly affects the speed and stability of the ship.

Based on the construction of the ship, the hull is the first area exposed to seawater. The hull is the main part of the ship's structure that functions to provide buoyancy and withstand ship loads. The hull is designed to withstand various types of loads. The hull is responsible for several important functions, viz: accommodating cargo and crew, resisting water forces such as being able to withstand various water forces, such as compressive, frictional, and wave forces, maintaining ship stability, and protecting the ship's contents, i.e. cargo and equipment from water, weather, and other damages (Helfman et al., 2019). Hull design involves selecting the right material, such as steel or aluminum, and effective construction methods, such as welding and plate fitting. In addition, the structural design must ensure strength and stability through careful calculations (Adiputra et al., 2023). Understanding these design principles is essential in maritime engineering education, as it equips students with the necessary skills to analyze, simulate, and optimize ship structures (Xiao et al., 2022).

The engine foundation structure is of concern to the author because the structure must support the load of the main engine and withstand various forces that occur to ensure the safety of the hull structure (Iovino et al., 2021). To calculate the maximum deflection in structures such as ships, partial differential equations (PDPs) of elasticity or plate and shell theory are often used (Arbind et al., 2021). One of the equations often used in this context is the thin plate theory developed by mathematicians such as Poisson and Navier (Lio et al., 2020). It is necessary for students who are studying shipbuilding and marine engineering courses to learn these engineering and mathematical concepts (Kara, 2021). By incorporating advanced simulation tools and computational models into the learning process, students can better comprehend real problems in shipbuilding and hydrodynamic analysis (Hontvedt & Øvergård, 2020). This combination of theoretical concepts with practical implementation aids in the development of problem-solving skills, critical thinking, and innovation in maritime engineering (Acciaro & Sys, 2020).

Simulations in education are a critical element to enhance students' understanding in terms of ship design and structural analysis (Muliyati et al., 2023). Students are able to visualize complex hydrodynamic interactions and structural responses under different conditions using computer-based simulations. (Li et al., 2020) For example, FEA and CFD software allow students to simulate several hull designs and plate thickness variations under hydrostatic pressure. Such simulators enable students to experiment with different design cases without the need to develop costly physical models, enhancing learning and making it more interactive and effective.

Educational simulation also provides a risk-free medium through which students can experiment with engineering concepts and make decisions based on facts (Motejlek & Alpay, 2023).

In maritime education, such simulations could be incorporated into project-based learning, where students apply themselves to actual case studies of hull deflection, stress distribution, and material selection (Loddé et al., 2019; Jamil & Bhuiyan, 2021). By means of interactive virtual experiments, students acquire basic engineering skills such as data interpretation, design enhancement, and fault analysis (Lanzo et al., 2020; Martin-Villalba & Urquia, 2022). Beyond improving concept mastery, this practice prepares students to pursue future professions in industry via bridging concepts and applications.

The partial differential equation that describes the deflection (w(x,y)) of a thin plate made of elastic material under load is:

$$D\left(\frac{(\partial^4 w)}{(\partial x^4)}+2\frac{(\partial^4 w)}{(\partial x^2\partial y^2)}+\frac{(\partial^4 w)}{(\partial y^4)}\right)=q(x,y)$$

where:
w: the displacement (deflection) of the plate at a point with coordinates $(x,\ y)$. Specifically, it describes how the plate bends or flexes under an applied load.
D: the flexural rigidity of the slab, which depends on the material properties of the slab and its thickness. Mathematically, D can be expressed as: $D=\frac{Eh^3}{12(1-v^2)}$
where:
- E is the modulus of elasticity of the material (Young's modulus),
- h is the thickness of the plate,
- v is the Poisson's ratio of the material.
q(x, y): load applied to the plate at a point with coordinates (x,y). This load can be distributional (e.g. pressure) or unevenly distributed across the surface of the plate.

This equation states that the result of a complex differential operation on the deflection w, involving the fourth derivative, multiplied by the bending stiffness D, is equal to the load q(x,y) applied to the plate. Plate design selection and planning is one of the solutions to withstand the load on the ship, so that the ship does not experience corrosion, stress, strain, deflection, and other problems that can damage the structure and condition of the ship. Maintenance of the ship structure is also very important to prevent the reduction of plate thickness during ship operation. Because if the ship plate is getting thinner, the stress that occurs on the ship will be greater [6].

Figure 1. Ro-Ro Ferry.

In 1950 there were many innovations in cargo handling that focused on ship design development. One of them that was successfully developed was the Ro-Ro Ferry. The ferry is one type of ship that sails at short distances or ships that sail from one island to another, so it is also known as a crossing ship. Ferries that are designed with two ramp doors, namely the front door and the back door, are Ro-Ro type ferries or an abbreviation of roll on-roll off (Ro-Ro) [8]. Ro-Ro ships are ships designed to load vehicles that can enter and exit the ship with their own drive, so they are called roll on-roll off (Ro-Ro) ships. This ship can carry trucks, passengers, and cars. The characteristics of this ship include ramp access at the front (bow) and back (stern), having a vehicle deck with a long lane, and many ventilators on the deck for the exhaust of vehicle fumes during loading and unloading.

In addition, hydrostatic factors are an important aspect in ship design and operation. Hydrostatic pressure is the pressure caused by the force on the liquid against an area of pressure field at a certain depth. Hydrostatic pressure is pressure that is not influenced by the density of the container, but is influenced by the density of the liquid, the surrounding air, the acceleration of gravity and the depth of the object in the liquid. Hydrostatic pressure is also caused by the force that exists in the liquid against an area of the pressure field at a certain depth. A point in the liquid located at a depth of h from the surface of the liquid experiences the weight of the liquid above it. The gravity is evenly distributed over a cross-sectional area A resulting in hydrostatic pressure, ie:

$$P = \rho . g . h$$

Details :

P = hydrostatic pressure (N/m^3 atau Pa)

ϱ = density (kg/m^3)

g = acceleration of gravity (m/s^2)

h = depth (m).

Hydrostatics includes several critical concepts such as hydrostatic pressure, which is the pressure experienced by the bottom of a ship due to the weight of the water above it, and buoyancy, which is the force that pushes a ship upwards so that it can float. Ship stability is also a major concern, ensuring that the ship remains balanced and can return to its original position after being tilted due to loads or external disturbances such as waves. This stability is strongly influenced by the ship's center of gravity and metacentric point. Ship stability is also highly dependent on several factors including the dimensions of the ship, the shape of the ship's body in the water, the distribution of objects on the ship, and the angle of inclination of the ship to the horizontal plane.

On the other hand, seawater depth affects the material properties of ships and their operational conditions. Changes in pressure at different depths can affect the strength, ductility and durability of materials used in ship construction. For example, steel commonly used in ship construction may undergo changes in mechanical properties under high stress at extreme sea depths, which may result in deformation and structural damage. In addition, the compression effect, where materials are compressed when at greater depths, can produce internal stresses and deformations in ship structures. Therefore, ship design must take this factor into account to avoid damage due to significant pressure changes. Vessels operating at various depths require adaptation to extreme pressures, such as submarines that must be designed to withstand very high pressures at ocean depths, as well as surface vessels operating at shallow depths that must consider lower pressure conditions and their effects on materials.

To calculate the hull deflection due to hydrostatic pressure at various seawater depths, the Kirchhoff-Love equation is used. This equation takes into account the bending deformation of thin plates and is expressed as follows:

$$[D\nabla^4 w = q]$$

where:

D : the flexural rigidity of the slab, given by $D = \frac{Eh^3}{12(1-v^2)}$

w : plate deflection

q : applied load per unit area

∇^4 : biharmonic operator

In this context, the hydrostatic pressure at a given depth is calculated using the formula:

$$q = \rho_{air}.\ g\ .\ h$$

where:

ρ_{air} : seawater density

g : acceleration of gravity

h : water depth

Using the Kirchhoff-Love equation, the hull deflection of a Ro-Ro Ferry can be modeled and analyzed for various conditions of water depth and plate thickness. This analysis helps in ensuring the design of a strong and safe ship structure to deal with varying hydrostatic pressure.

Based on the above description, the purpose of this simulation is to determine the hull deflection of the Ro-Ro Ferry due to hydrostatic pressure. This simulation was conducted with two variations: 1) different plate thicknesses at a fixed depth of 10 meters, and 2) different seawater depths with a fixed plate thickness of 20 mm.

METHOD

Modeling the plate deflection of the Ro-Ro Ferry due to hydrostatic pressure at a depth of 10 meters using the finite difference method. Some physical and geometric parameters of the ship are set, such as steel elastic modulus (E), Poisson's ratio (ν), ship length (L), seawater density (ϱ), and gravitational acceleration (g). Then, a discrete grid along the ship is created with a certain number of discrete points (num_points). The variation of plate thickness is tested to see its effect on plate deflection.

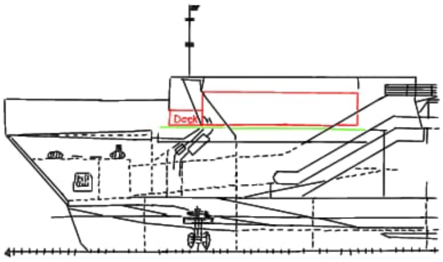

Figure 2. Ship structure

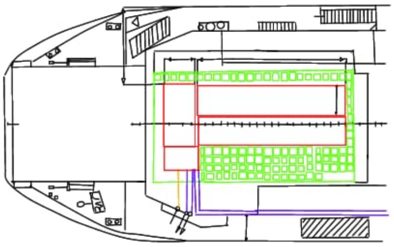

Figure 3. Ship plate structure

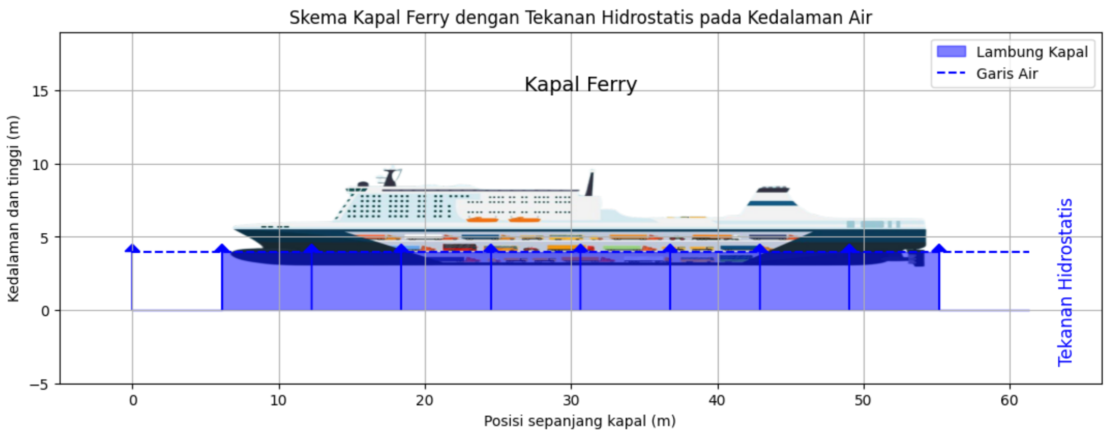

Figure 4. Ferry Schematic with Hydrostatic Pressure at Water Depth

For each slab thickness, the flexural stiffness (D) is calculated using the formula $D = \frac{Eh^3}{12(1-\nu^2)}$. Furthermore, the stiffness matrix (K) and load vector (F) are constructed based on the applied hydrostatic pressure. The boundary condition set is zero deflection at both ends of the plate. A system of linear equations Kw = F is then solved to obtain the deflection (w) along the plate.

The deflection results for each plate thickness are plotted in a graph for visualization, showing how the plate thickness affects the deflection due to hydrostatic pressure. This code provides important insights into the structural response of ship plates to pressure loads, which is critical to the design and safety of ship structures.

The algorithm used to determine these results is as follows:

1. Start
2. Determine physical and geometric parameters
3. Form a discrete grid
4. Calculating hydrostatic pressure
5. Defining the function to calculate the bending stiffness of the plate
6. Initiating the plot
7. Iterating through various plate thicknesses
8. Configuring and displaying the plot
9. Finish

RESULTS AND DISCUSSION

2D Hull Model:

The hull can be modeled as a thin plate with a length of 61.3 meters and a height of 10 meters from the waterline. Discretization is done by dividing the plate into small elements (mesh) so that it can be calculated numerically. A tighter mesh is applied in areas with significant pressure or deflection changes to improve the accuracy of the results.

Load Application

Hydrostatic pressure is applied to the outer surface of the hull. The pressure can change with water depth, for this case the depth is set at 10 meters below sea level with various plate thicknesses. The hydrostatic load can be calculated by the formula:

$$P = \rho g h$$

where:

ρ = Density of seawater (kg/m^3)

g = Gravitational acceleration (m/s^2)

h = depth

Simulation Results:

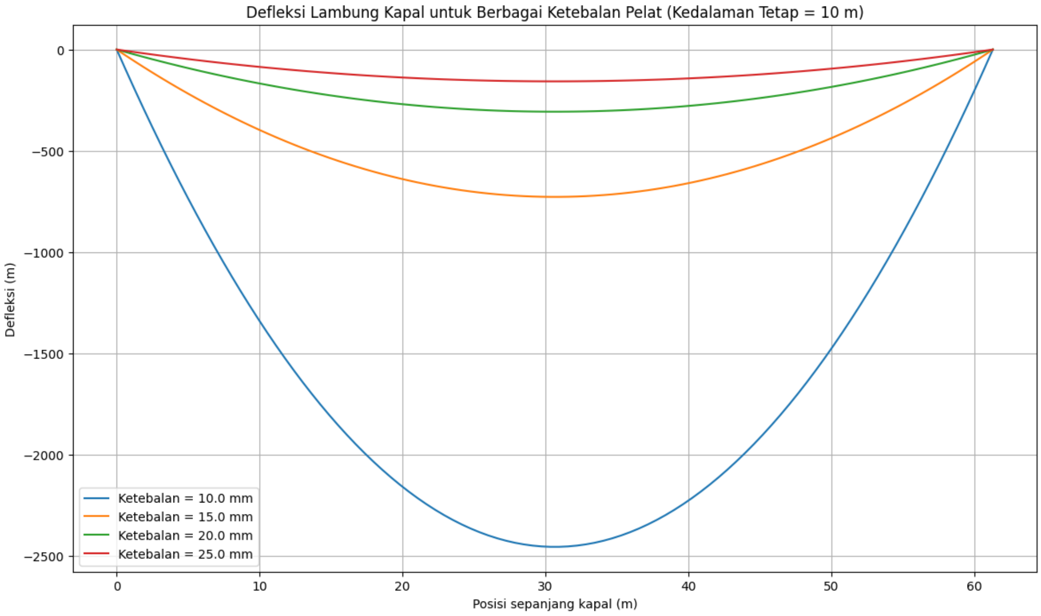

Figure 5. Hull Deflection for Various Plate Thicknesses (Fixed Depth = 10 m)

The graph generated through the simulation shows the hull deflection due to hydrostatic pressure for various hull plate thicknesses at a fixed depth of 10m. The plate thicknesses tested were 10.0 mm, 15.0 mm, 20.0 mm and 25.0 mm. The graph above displays the deflection along the length of the 61.3-meter ship, with the largest deflection occurring at the center of the ship.

It can also be seen in the graph that the hull deflection decreases as the plate thickness increases. The plate with a thickness of 10.0 mm shows the largest deflection, reaching about 2400 meters amidships. On the other hand, the plate with a thickness of 25.0 mm shows the smallest deflection, only about < 500 meters amidships. The resulting deflection pattern is parabolic, with the maximum deflection point at the center of the ship, since the largest hydrostatic pressure distribution also occurs at the center of the ship while the deflection at both ends of the ship is zero. This corresponds to the boundary conditions applied in the simulation.

Greater plate thickness results in smaller deflection. Thicker plates have greater stiffness, making them more resistant to bending due to hydrostatic pressure.

It can be concluded that the thickness of the plate greatly affects the deflection of the ship structure. Thicker plates can resist deformation better than thin plates. This is important in ship structure design, as the use of thicker plates in high stress areas can improve the safety integrity of the ship.

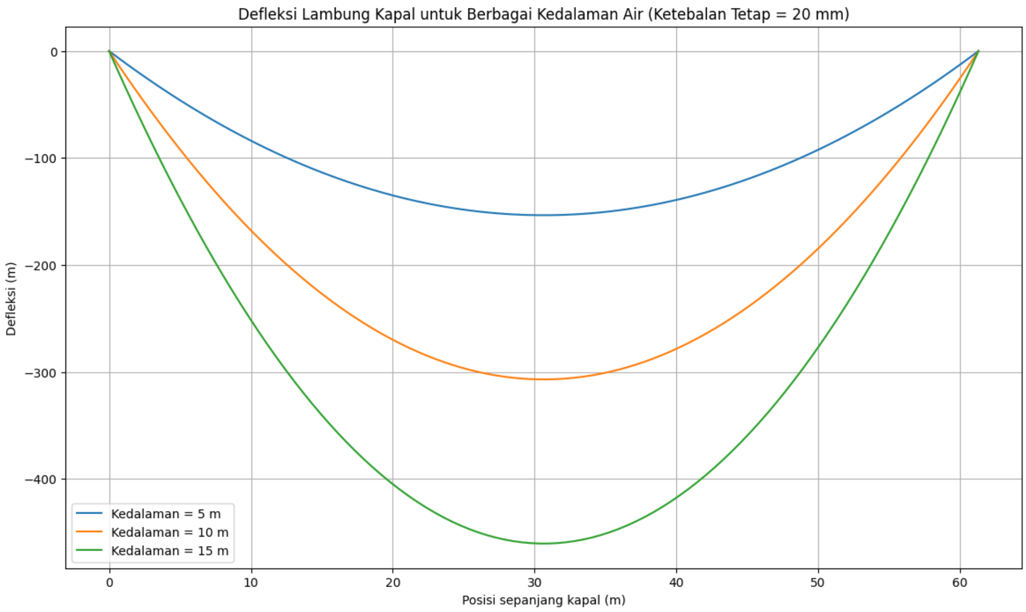

Figure 6. Hull Deflection for Various Water Depths (Fixed Thickness = 20 mm)

The graph generated through the simulation shows the hull deflection due to hydrostatic pressure for various water depths with a fixed hull plate thickness of 20 mm. The tested water depths are 5 m, 10 m, and 15 m. The graph above displays the deflection along the length of the 61.3 m long ship, with the largest deflection occurring at the center of the ship.

It can be seen in the graph that the hull deflection increases as the water depth increases. At a water depth of 5 m (blue line), the maximum deflection reaches about 150 m amidships. At a water depth of 10 meters (orange line), the maximum deflection reaches about 300 m amidships. While at a water depth of 15 meters (green line), the maximum deflection reaches about 450 m amidships.

The resulting deflection shape resembles a parabola, with the maximum deflection at the center of the vessel. This occurs because the greatest hydrostatic pressure is at the center of the vessel, while at both ends of the vessel, the deflection reaches zero. This pattern corresponds to the boundary conditions applied in the simulation.

It can be concluded that water depth greatly affects the deflection of the ship structure. Greater deflection occurs at deeper water depths, due to greater hydrostatic pressure. This is important in the design of ship structures, as the use of stronger materials or more robust designs may be required in operating conditions with greater water depths to maintain the integrity and safety of the ship.

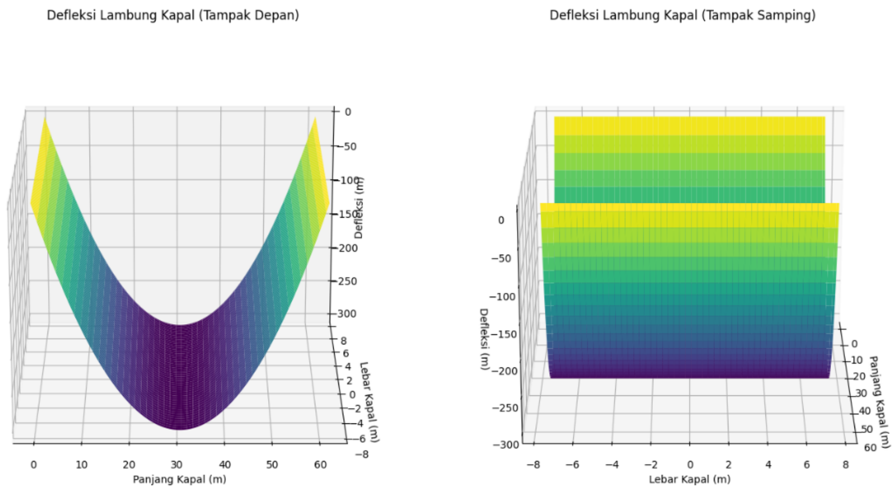

Figure 7. 3D Graph for Hull Deflection (front view and side view)

This 3D illustration is only to illustrate the extent to which plate deflection occurs. The thickness of the plate is made different because the main objective in this journal is to find the safest plate thickness for a Ro-Ro Ferry vessel. The water depth is an additional condition to test the plates that have been considered optimal. The test is carried out to find out whether the deflection of the plate is still in the safe category if it is carried out in deeper water conditions.

The left graph shows a front view of the hull deflection, with the horizontal axis representing the vessel length in meters and the vertical axis representing the vessel width in meters. The vessel deflection is represented by color, where purple indicates maximum deflection and yellow indicates minimum deflection. The deflection pattern is parabolic with the maximum deflection occurring at the center of the ship.

The right graph displays a side view of the hull deflection, with the horizontal axis representing the width of the vessel in meters and the vertical axis representing the length of the vessel in meters. The colors on this graph also indicate the degree of deflection, similar to the left graph. This parabolic deflection pattern indicates that the greatest hydrostatic pressure occurs at the center of the ship, while the deflection at both ends of the ship reaches zero, in accordance with the boundary conditions applied in the simulation.

CONCLUSION

This study shows that hull deflection due to hydrostatic pressure is strongly influenced by plate thickness and water depth. Simulation results show that increasing the plate thickness from 10.0 mm, 15.0 mm, 20.0 mm to 25.0 mm, significantly reduces the hull deflection, with the maximum deflection from about 2400 mm decreasing to less than 500 mm. In addition, the water depth also affected the deflection, where an increase in depth from 5 m, 10 m, and 15 m, caused the maximum deflection to increase from about 150 mm to 450 mm. The deflection pattern is parabolic with the maximum deflection occurring at the center of the vessel, as the largest hydrostatic pressure distribution is at the center of the vessel. Therefore, in order to maintain the integrity, strength and safety of the ship structure, it is important to consider a larger plate thickness and a stronger design, especially under operating conditions with deeper water depths.

REFERENCES

References

Acciaro, M., & Sys, C. (2020). Innovation in the maritime sector: aligning strategy with outcomes. *Maritime Policy & Management*, *47*(8), 1–19. https://doi.org/10.1080/03088839.2020.1737335

Adiputra, R., Yoshikawa, T., & Erwandi, E. (2023). Reliability-based assessment of ship hull girder ultimate strength. *Curved and Layered Structures*, *10*(1). https://doi.org/10.1515/cls-2022-0189

Arbind, A., Reddy, J. N., & Srinivasa, A. R. (2021). A general higher-order shell theory for compressible isotropic hyperelastic materials using orthonormal moving frame. *ArXiv (Cornell University)*, *122*(1). https://doi.org/10.48550/arxiv.1912.13310

Helfman, N., Nishri, B., & Cvikel, D. (2019). Finite Element Analysis of Shell-First and Longitudinally Reinforced Frame-Based Wooden Ships. *Journal of Maritime Archaeology*, *14*(2), 291–309. https://doi.org/10.1007/s11457-019-09233-0

Hontvedt, M., & Øvergård, K. I. (2020). Simulations at Work —a Framework for Configuring Simulation Fidelity with Training Objectives. *Computer Supported Cooperative Work (CSCW)*, *29*(1-2), 85–113. https://doi.org/10.1007/s10606-019-09367-8

Iovino, M., Di Laora, R., & de Sanctis, L. (2021). Serviceability analysis of piled foundations supporting tall structures. *Acta Geotechnica*, *16*(12), 3963–3973. https://doi.org/10.1007/s11440-021-01340-4

Jamil, M. G., & Bhuiyan, Z. (2021). Deep learning elements in maritime simulation programmes: a pedagogical exploration of learner experiences. *International Journal of Educational Technology in Higher Education*, *18*(1). https://doi.org/10.1186/s41239-021-00255-0

Kara, F. (2021). Application of time-domain methods for marine hydrodynamic and hydroelasticity analyses of floating systems. *Ships and Offshore Structures*, *17*(7), 1628–1645. https://doi.org/10.1080/17445302.2021.1937798

Lanzo, J. A., Valentine, A., Sohel, F., Yapp, A. Y. T., Muparadzi, K. C., & Abdelmalek, M. (2020). A review of the uses of virtual reality in engineering education. *Computer Applications in Engineering Education*, *28*(3), 748–763. https://doi.org/10.1002/cae.22243

Li, J., Jiang, X., Singh, A., Heinonen, O. G., Hernández-Ortiz, J. P., & Juan, J. (2020). Structure and dynamics of hydrodynamically interacting finite-size Brownian particles in a spherical cavity: Spheres and cylinders. *The Journal of Chemical Physics*, *152*(20). https://doi.org/10.1063/1.5139431

Lio, F. D., Palmurella, F., & Rivière, T. (2020). A Resolution of the Poisson Problem for Elastic Plates. *Archive for Rational Mechanics and Analysis*, *236*(3), 1593–1676. https://doi.org/10.1007/s00205-020-01499-2

Loddé, B., Querellou, G.-E., Morel, A., & L'Her, E. (2019). SEA-mulation: training for technical treatment related to emergency situations in maritime environment. *Critical Care*, *23*(1). https://doi.org/10.1186/s13054-019-2599-y

Martin-Villalba, C., & Urquia, A. (2022). An approach to develop collaborative virtual labs in Modelica. *IEEE Access*, *10*, 58938–58949. https://doi.org/10.1109/access.2022.3179712

Motejlek, J., & Alpay, E. (2023). The retention of information in virtual reality based engineering simulations. *European Journal of Engineering Education*, *48*(5), 929–948. https://doi.org/10.1080/03043797.2022.2160968

Muliyati, D., Purwahida, R., Yanez, M. A., Permana, H., Sabrina, P. M., Zain, N. T., Sholina, W., & Rachman, G. W. (2023). The Training of STEM-Robotic as Project-Based Learning for Elementary Schools. *Prosiding Seminar Penelitian Dan Pengabdian Kepada Masyarakat*, *1*(1), 41–48. https://doi.org/10.58797/sppkm.01.06

Takami, T., Komoriyama, Y., Ando, T., Ozeki, S., & Iijima, K. (2019). Efficient FORM-based extreme value prediction of nonlinear ship loads with an application of reduced-order model for coupled CFD and FEA. *Journal of Marine Science and Technology*, *25*(2), 327–345. https://doi.org/10.1007/s00773-019-00667-8

Xiao, S., Han, Y., Zhang, Y., Wei, Q., Wang, Y., Wang, N., Wang, H., Liu, J., & Liu, Y. (2022). A Reliability Analysis Framework of Ship Local Structure Based on Efficient Probabilistic Simulation and Experimental Data Fusion. *Metals*, *12*(5), 805–805. https://doi.org/10.3390/met12050805