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GEOMETRY-AWARE STRUCTURAL-DEMAND SCREENING AND VULNERABLE-REGION IDENTIFICATION FOR A SHIP HULL UNDER COUPLED HEAVE-PITCH MOTIONS

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ABSTRACT

This paper presents a geometry-aware structural-demand screening framework for a ship hull subjected to coupled heave–pitch motions in head seas. The work addresses the need to move beyond hydrodynamic susceptibility alone toward hull-resolved structural interpretation, particularly for large ships in which wave-induced motions produce concentrated bending, shear, stress and vulnerability patterns. Recent hydroelastic studies on large containerhips and segmented-model experiments have shown that vertical-plane response is closely linked to global structural consequences such as vertical bending moment, vertical shear force and local vulnerability concentration, especially in the low-frequency corridor associated with dominant heave–pitch response. Building on this foundation, the present study converts the coupled hydrodynamic-response basis into longitudinal bending-, shear- and stress-demand proxies and maps these quantities onto the ship’s hull geometry. Results indicate that the primary structural-demand corridor is centred in the midship and adjacent central hull span, while shear-sensitive behaviour remains relatively stronger toward the forward and aft ends. The integrated vulnerability field further reveals two mirrored side-surface hotspot bands in the central hull region rather than a single isolated critical point. The study demonstrates that coupled heave–pitch results can be transformed into a physically meaningful, geometry-aware structural-screening framework without requiring a full direct hydroelastic finite-element solution. This provides a practical bridge between hydrodynamic response analysis and subsequent resilience, mitigation and optimisation studies.

Keywords: Hydroelasticity; Heave–Pitch Coupling; Structural Demand Screening; Ship Hull Vulnerability; Geometry-Aware Mapping; Vertical Bending Moment; Shear Force

1 INTRODUCTION

Hydroelastic ship analysis concerns the transformation of wave-induced hydrodynamic response into structural consequence. For large, relatively flexible ships—especially container-ship-type hulls with long spans and large deck openings—this transformation is not adequately described by motion response alone. Coupled heave–pitch behaviour in head and near-head seas generates unfavourable structural-demand concentrations over the hull (Senjanović et al.,

2009). The vertical-plane response of such vessels is closely tied to global measures such as vertical bending moment, vertical shear force, and higher-frequency springing and whipping loads. Foundational and subsequent numerical and experimental studies (Malenica et al., 2014; Chen et al., 2017; Jiao et al., 2021) have shown that hydrodynamic and structural contributions cannot be cleanly separated once hull flexibility becomes significant.

A practical difficulty remains in many applied workflows. High-fidelity seakeeping tools generate rich motion and excitation data, yet these outputs do not automatically identify which parts of the hull are structurally most exposed. Full structural simulations may be expensive or unavailable at early design stages. Consequently there is a need for a geometry-aware structural-screening stage that translates coupled heave–pitch behaviour into spatially resolved demand indicators before finite-element refinement. This need is reinforced by the growth of digital twins and integrated hydro-structural workflows, which require a fast but physically interpretable mapping from response severity to structural criticality (Schirrmann et al., 2022; Palma et al., 2025).

While existing hydroelastic studies report global loads or experimental stress indicators, fewer combine those results with hull-surface mapping in a form directly useful for structural screening and later mitigation design. The present paper addresses this gap by converting the coupled heave–pitch response basis established in prior work into longitudinal demand proxies, mapping them onto the ship hull, aggregating them into combined vulnerability measures, and identifying critical stations and surface zones. The resulting framework occupies the intermediate layer between pure hydrodynamics and full structural analysis.

The results constitute a screening framework rather than a full direct hydroelastic finite-element solution. Hull-region ranking remains relatively coarse, and the comparatively weak directional variation of the global criticality heatmap may partly reflect the integrated formulation. These limitations are acknowledged and motivate the recommendations for future work.

Hydroelastic analysis of large containerhips has advanced through theoretical formulations (Senjanović et al., 2009; Malenica et al., 2014), segmented and fully elastic model experiments (Chen et al., 2017; Grammatikopoulos et al., 2021; Chen et al., 2024), and hybrid numerical methods including BEM–beam, CFD–FEM and modal superposition approaches (Wang et al., 2022; Zhang et al., 2024; Liu et al., 2025; Ma et al., 2024). Benchmark exercises continue to refine confidence in whipping predictions (Parunov et al., 2024). Parallel developments in data-driven and digital-twin modelling (Schirrmann et al., 2022, 2023; Palma et al., 2025) seek to embed physics-based structure into fast predictive tools. Despite these advances, a gap remains between the production of rich hydrodynamic response data and the rapid, geometry-resolved identification of structural demand concentrations suitable for early-stage screening. The present work occupies that intermediate layer.

2 MATERIALS AND METHODS

2.1 Ship geometry and material idealisation

The study is performed on the S-175 U-Waters container ship. Principal particulars are summarised in Table 1. Hull geometry was developed in Rhinoceros 3D; representative views are shown in Figures 1–3. Structural steel properties used for stress-proxy interpretation are Young’s modulus 2.0×10^{11} Pa, Poisson’s ratio 0.3, tensile yield strength 250 MPa and ultimate tensile strength 460 MPa. Environmental forcing corresponds to the wave-energy spectrum characteristic of the Forcados Oil Terminal offshore location (Figure 4).

Table 1: Principal particulars of the S-175 U-Waters container ship

Particular	DWT (t)	LWL (m)	B (m)	D (m)	T (m)	LOA (m)
S-175 U-Waters	11 456	170.57	25.39	11.0	5.0	182.68

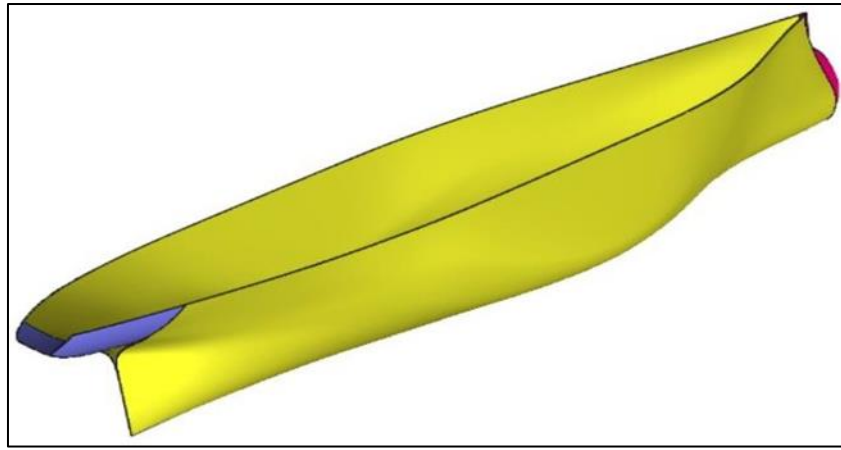


Figure 1: S-175 U-Waters container ship (Rhinceros 3D model).

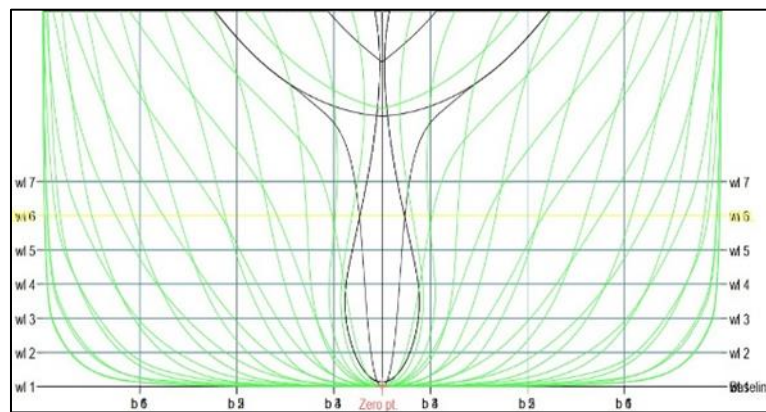


Figure 2: Body plan of the S-175 U-Waters container ship.

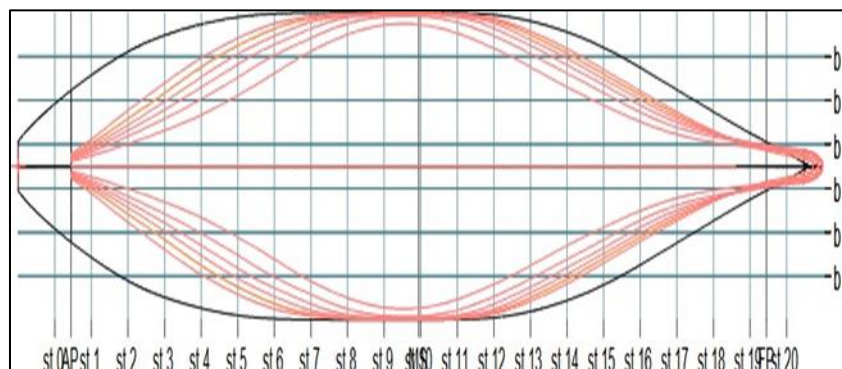


Figure 3: Plan view of the S-175 U-Waters container ship.

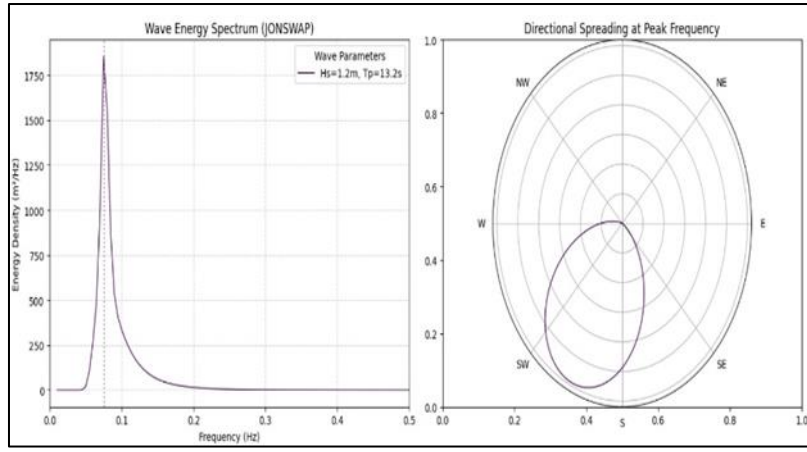


Figure 4: Wave energy spectrum at the Forcados Oil Terminal location.

2.2 Coupled-response-derived structural-demand basis

The structural screening is based on the coupled heave–pitch response established in previous work. Let the normalised heave and pitch response amplitude operators be denoted $RAO_3 \sim (\omega, \beta)$ and $RAO_5 \sim (\omega, \beta)$. A scalar coupled dynamic-severity driver is defined as

$$D_c(\omega, \beta) = w_3 RAO_3(\omega, \beta) + w_5 RAO_5(\omega, \beta) \quad (1)$$

where w_3 and w_5 are positive weighting coefficients that sum to unity. For longitudinal structural-demand screening this dynamic-severity information is projected along the hull length using the ship-based station coordinate x . The normalised longitudinal position is

$$\bar{x} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (2)$$

A bending-demand proxy is defined as

$$M_p(x) = D_0 [a_0 + a_1 \sin^2(\pi \bar{x}) + a_2 \bar{x}] \quad (3)$$

where D_0 is a representative scalar severity level derived from the coupled response basis and a_0, a_1, a_2 are shaping constants chosen to reproduce the characteristic midship concentration of vertical bending moment. The shear-demand proxy is defined as

$$Q_p(x) = D_0 [b_0 + b_1 |\cos(\pi \bar{x})| + b_2 (1 - \bar{x})] \quad (4)$$

with coefficients b_0, b_1, b_2 selected to emphasise elevated shear near the ends. A combined stress-like structural-demand proxy is then formed as

$$\sigma_p(x) = c_1 M_p(x) + c_2 Q_p(x) \quad (5)$$

where $c_1 + c_2 = 1$ and $c_1, c_2 \geq 0$. Each of the three longitudinal demand measures is subsequently normalised to the unit interval:

$$M_p(x) = \frac{M_p(x) - M_{p,min}}{M_{p,max} - M_{p,min}} \quad (6)$$

$$Q_p(x) = \frac{Q_p(x) - Q_{p,min}}{Q_{p,max} - Q_{p,min}} \quad (7)$$

$$\tilde{\sigma}_p(x) = \frac{\sigma_p(x) - \sigma_{p,min}}{\sigma_{p,max} - \sigma_{p,min}} \quad (8)$$

2.3 Hull-surface mapping onto ship geometry

Let the ship hull mesh be represented by a vertex set $\{v_i\}$ ($i = 1$ to N_v) and a face set $\{F_k\}$. Each vertex is defined by its Cartesian coordinates $v_i = (x_i, y_i, z_i)^T$. The station-based structural-demand proxy is mapped from longitudinal space onto vertices by one-dimensional interpolation along the x -coordinate:

$$d_v(i) = I(x_i; x_s, \sigma_p(x_s)) \quad (9)$$

where x_s denotes the discrete longitudinal station positions and I denotes linear (or higher-order) interpolation. A bending-like hull field is obtained by normalising the mapped field, $B_h(i) = d_v(i)$. To account for lateral and vertical variation of structural exposure, normalised geometric coordinates are introduced:

$$\bar{y}_i = \frac{|y_i| - \min|y|}{\max|y| - \min|y|} \quad (10)$$

$$\bar{z}_i = \frac{|z_i| - \min|z|}{\max|z| - \min|z|} \quad (11)$$

A stress-like hull field is then constructed as

$$S_h(i) = \alpha_1 d_v(i) + \alpha_2 \bar{y}_i + \alpha_3 \bar{z}_i \quad (12)$$

where $\alpha_1 + \alpha_2 + \alpha_3 = 1$ and all weights are non-negative. The normalised version of S_h supplies the three-dimensional hull stress-demand contours.

2.4 Combined vulnerability construction and ranking

A combined criticality field integrates hydrodynamic and structural information. Let d_v denote the normalised dynamic-to-structural mapping and let C_s denote a structural criticality field. The combined criticality is written

$$C(i) = \gamma_1 d_v(i) + \gamma_2 C_s(i) \quad (13)$$

with $\gamma_1 + \gamma_2 = 1$. The final hull vulnerability index is obtained by normalising C to the unit interval. Station-wise structural criticality is defined by averaging the vulnerability index over all vertices belonging to each longitudinal station; the critical station is the station of maximum average criticality. Top-vulnerable hull zones are extracted by percentile thresholding: vertices whose vulnerability exceeds the 90th percentile of the field are retained as the hotspot set. The global coupled criticality heatmap is constructed over the discrete frequency and heading sets after structuralisation and normalisation of Equation (1).

3 RESULTS AND DISCUSSION

3.1 Longitudinal structural-demand trends

The bending-demand proxy (Figure 5) rises from a low level near the bow, grows steadily toward the middle of the hull, reaches a maximum slightly above 1.25, and then declines aft. The principal peak occurs in the central span, approximately around the midship to aft-central transition. This indicates that the coupled heave-pitch motion basis translates into a strongly centralised global bending-type structural-demand corridor.

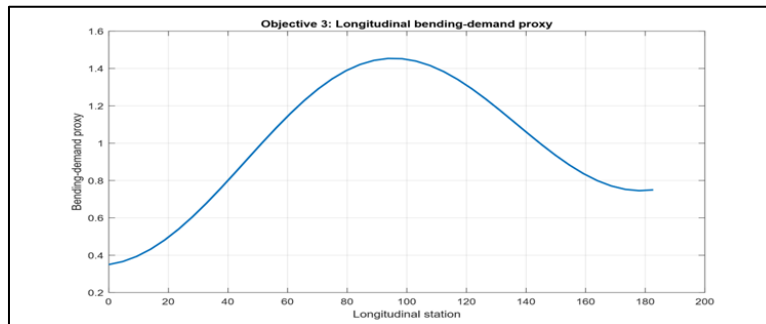


Figure 5: Longitudinal bending-demand proxy.

The shear-demand proxy (Figure 6) behaves differently. It begins near 1.0 at the forward end, drops to approximately 0.30 near midships, and recovers to 0.70–0.75 toward the stern. Consequently the same hydrodynamic response basis produces a structurally different spatial distribution according to the demand measure considered: the central hull is most significant for bending-related demand, whereas the ends remain relatively more significant for shear-related demand.

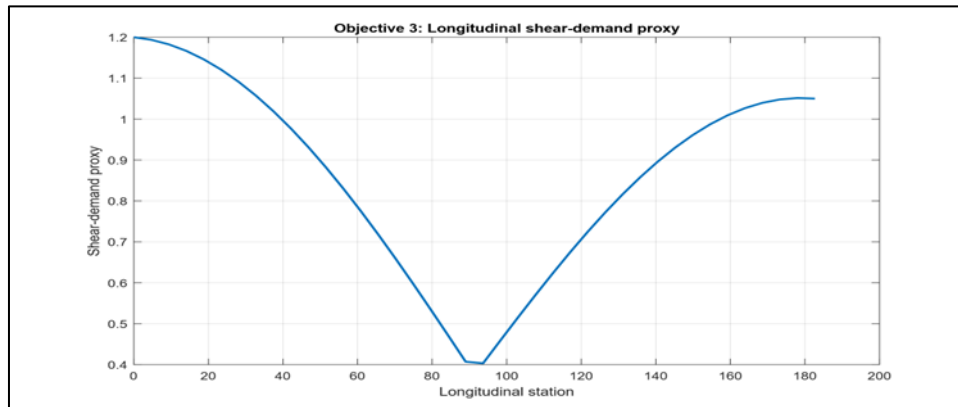


Figure 6: Longitudinal shear-demand proxy.

The stress-proxy distribution (Figure 7) combines aspects of both previous trends but remains dominated by the central span. The curve rises from approximately 0.18 near the forward end to just above 1.0 in the central corridor, forming a broad high-demand zone rather than a single isolated peak. The central vulnerable region is therefore better interpreted as an extended corridor than as one critical station.

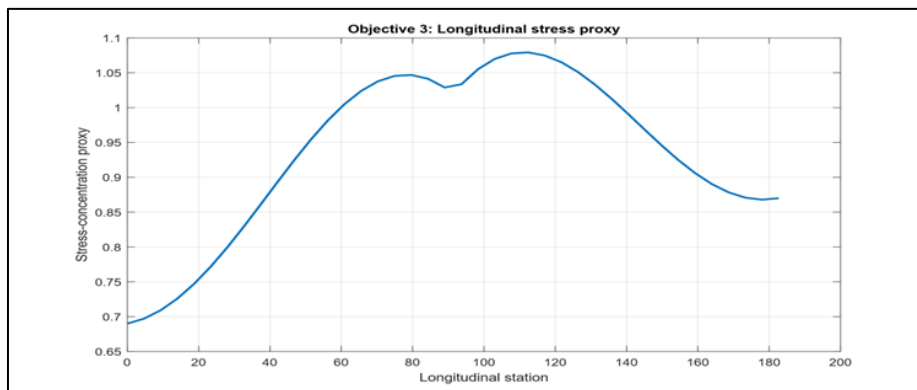


Figure 7: Longitudinal stress-demand proxy.

3.2 Hull-surface criticality mapping

The three-dimensional hull bending-demand contour (Figure 8) confirms the one-dimensional bending-demand result spatially: highest values are concentrated in the central hull span while bow and stern remain cooler. The hull stress-demand contour (Figure 9) exhibits the same central dominance but with broader lateral spread over the hull surface, indicating that the stress-like structural consequence of the coupled heave–pitch basis is not purely longitudinal.

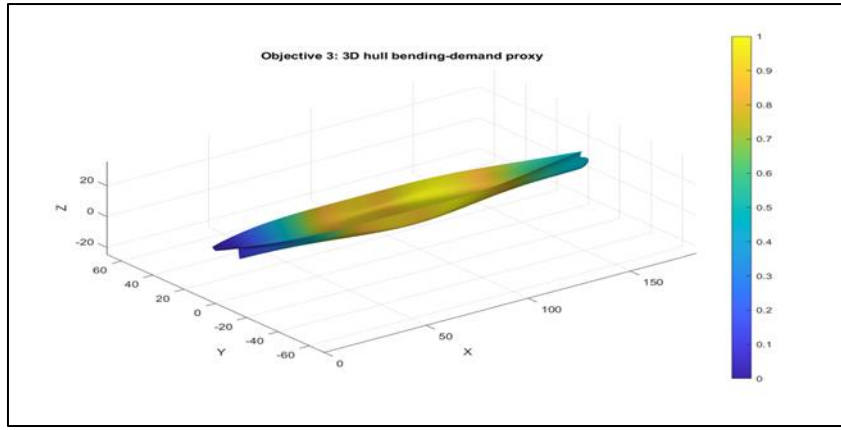


Figure 8: Three-dimensional hull bending-demand contour.

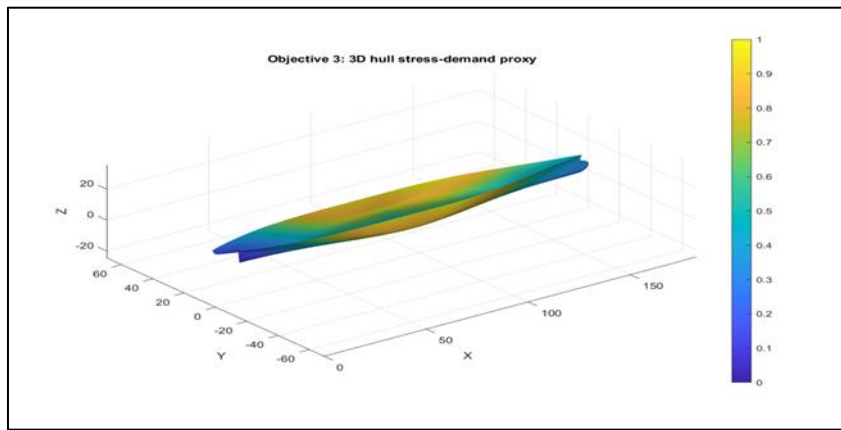


Figure 9: Three-dimensional hull stress-demand contour.

The integrated hull vulnerability map (Figure 10) combines the response-informed and structuralised fields into a single screening-level quantity. The most vulnerable region remains centred over the same structural corridor already identified by the longitudinal stress proxy, thereby validating rather than contradicting the one-dimensional interpretation.

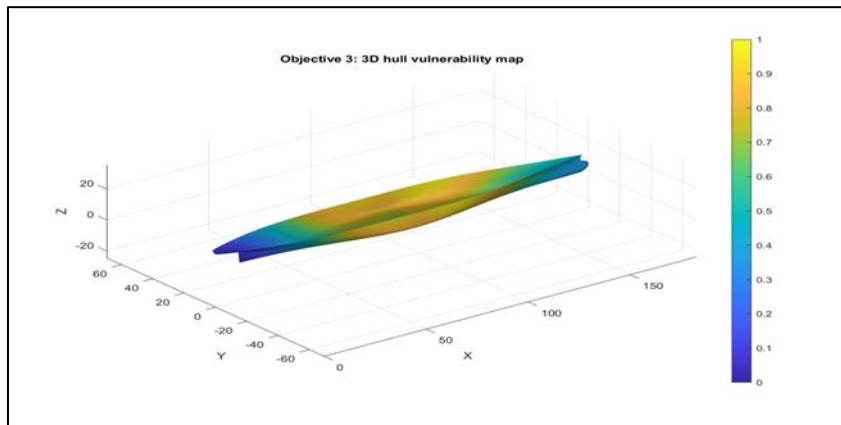


Figure 10: Three-dimensional hull vulnerability map.

3.3 Global criticality and ranking

The global criticality heatmap (Figure 11) shows that integrated structural criticality is concentrated primarily in a middle portion of the frequency axis, while variation across direction is comparatively weak. Once the coupled hydrodynamic response has been transformed into a structural-demand screening quantity, the dominant

discriminator becomes the frequency band rather than heading—an important transition from the more direction-sensitive hydrodynamic view developed in earlier papers of the series.

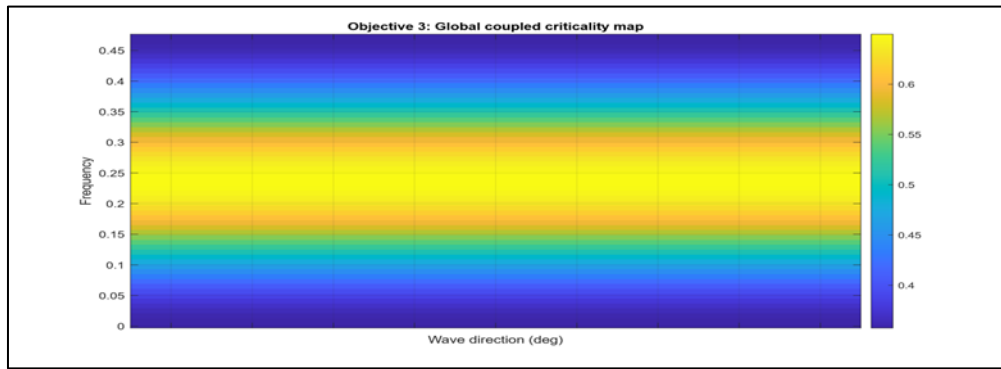


Figure 11. Global coupled criticality heatmap.

Hull-region ranking (Figure 12) currently resolves only the whole hull as one aggregated structural class; although this limits fine regional comparison it still confirms that structuralised vulnerability is globally elevated. By contrast the station-wise ranking (Figure 13) is highly informative: criticality rises from low values near the forward end to a broad maximum near the central hull (approaching 1.0) and then decreases toward the stern, quantitatively confirming the dominance of the central corridor.

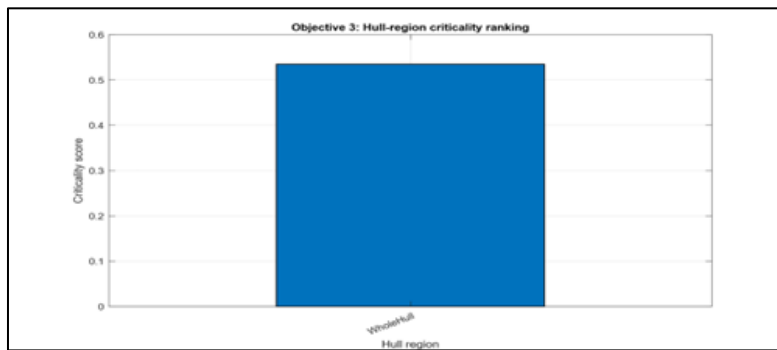


Figure 12: Hull-region ranking.

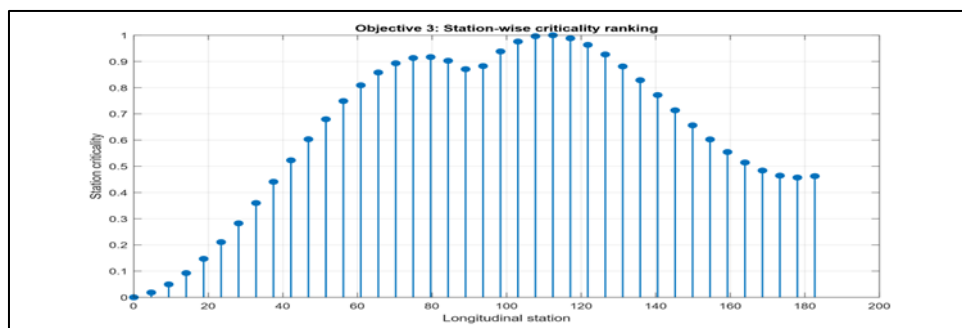


Figure 13: Station-wise criticality ranking.

3.4 Local vulnerable hull zones

The top-vulnerable-zone plot (Figure 14) constitutes one of the strongest results of the study. The highest-percentile vulnerability does not appear randomly over the hull; instead it forms two mirrored elongated bands on the port and starboard sides of the central hull region. Local structural screening is therefore not purely a question of midship location in one dimension: the vulnerable zones possess a distinct surface geometry and appear as paired side-dominant pathways.

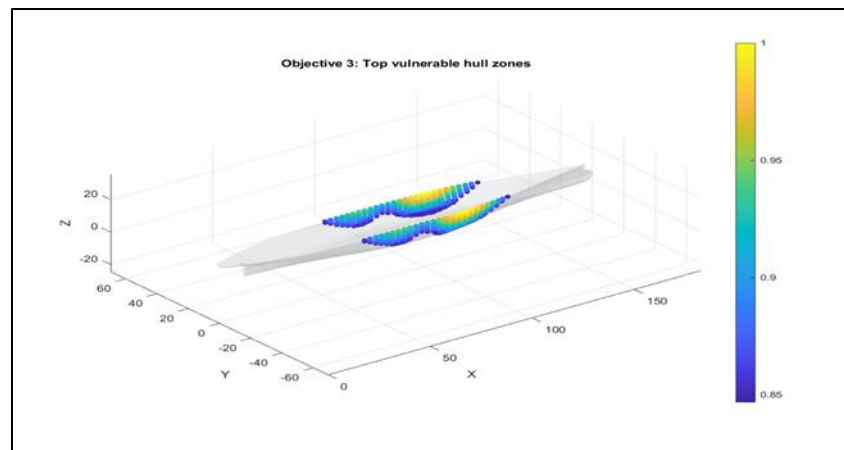


Figure 14: Top-vulnerable hull zones (90th-percentile threshold).

4 CONCLUSIONS

This paper has demonstrated that the coupled heave–pitch hydrodynamic response can be translated into a geometry-aware structural-demand screening framework over the hull. The core results show that the vessel’s most important structural corridor lies in the central hull span, that shear-sensitive behaviour remains relatively stronger toward the ends, and that the most vulnerable local zones appear as mirrored side-surface bands rather than a single isolated hotspot. The work therefore supplies the structural bridge between earlier hydrodynamic-response studies and subsequent investigations of resilience, mitigation and optimisation.

Future work should (i) connect the present maps directly to sectional loads, nodal stresses and finite-element-based structural response, (ii) refine regional aggregation so that multiple hull zones are ranked explicitly, and (iii) employ the identified central corridor and mirrored hotspot bands as direct targets in mitigation and optimisation studies.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

REFERENCES

- [1] Chang, X., Li, Y., Lu, Y., Yang, H., Chen, J., Wang, H., & Li, C. (2025). Experimental and numerical investigation on springing and whipping of an ultra-large 21000 TEU containership in head regular waves. *Ocean Engineering*, 328, 121538.
- [2] Chen, Y., Li, Y., Lu, Y., Wang, J., Yang, H., & Li, C. (2024). Design, construction and testing of a fully elastic ship model for hydro-elastic experiments in waves. *Marine Structures*, 96, 103612.
- [3] Chen, Z., Wang, P., Papanikolaou, A., Gu, X., & Liu, L. (2017). Time-domain numerical and segmented ship model experimental study on springing and whipping loads of a large containership in oblique waves. *Applied Ocean Research*, 67, 1–19.
- [4] Chen, Z., Lu, Y., Li, Y., Yang, H., & Li, C. (2024). Numerical and experimental study of asymmetrical wave impact and hydroelastic responses of an ultra-large container ship in oblique waves. *Applied Ocean Research*, 146, 103977.
- [5] Grammatikopoulos, A., Kapsenberg, G., Aalberts, P., & Moan, T. (2021). The design and commissioning of a fully elastic model for measuring global hydroelastic responses of large ships. *Marine Structures*, 79, 103041.
- [6] Im, H.-I., Vladimir, N., Malenica, Š., & Cho, D.-S. (2017). Hydroelastic response of 19,000 TEU class ultra large container ship with novel mobile deckhouse for maximizing cargo capacity. *International Journal of Naval Architecture and Ocean Engineering*, 9(3), 239–248.
- [7] Jiao, J., Yu, Y., Ren, H., & Gu, X. (2021). Vertical and horizontal bending moments on the hydroelastic segmented model of an ultra large container vessel in oblique waves. *Marine Structures*, 79, 103015.

- [8] Kim, Y., Hong, J. Y., Kim, B. W., & Kim, K. H. (2018). Analysis on the full scale measurement data of 9400TEU containership for hydroelastic vibration. *Marine Structures*, 58, 195–213.
- [9] Liu, R., Zhang, Z., Wen, Y., & Duan, W. (2025). Prediction of global structural responses for an ultra-large container ship at arbitrary locations using generalized modal superposition. *Ocean Engineering*, 318, 119643.
- [10] Lu, Y., Li, Y., Yang, H., Chen, J., Wang, H., & Li, C. (2025). Research on load design for large containership based on nonlinear hydroelastic response in waves. *Marine Transportation Engineering*, 6, 100245.
- [11] Ma, B., Lu, Y., Li, Y., Wang, H., & Li, C. (2024). Hydroelasticity of a 21000 TEU containership under freak wave conditions using a CFD-FEM two-way coupled method. *Ocean Engineering*, 308, 118107.
- [12] Malenica, Š., Senjanović, I., Vladimir, N., & Tomić, M. (2014). Hydro-structural issues in the design of ultra large container ships. *International Journal of Naval Architecture and Ocean Engineering*, 6(4), 878–895.
- [13] Palma, G., Serani, A., Aram, S., Wundrow, D. W., Drazen, D., & Diez, M. (2025). Bayesian Hankel dynamic mode decomposition for ship motion digital twinning. *Applied Ocean Research*, 154, 104541.
- [14] Parunov, J., Vukčević, V., & Senjanović, I. (2024). Benchmark on the prediction of whipping response of a warship model in regular waves. *Marine Structures*, 93, 103493.
- [15] Qi, Y., Zhang, Y., & Chen, X. (2026). A hybrid CFD-DNN framework for ship motion prediction in irregular waves and structural-operability assessment. *Ocean Engineering*, 347, 122574.
- [16] Rajendran, S., Fonseca, N., & Guedes Soares, C. (2015). Effect of surge motion on the vertical responses of ships in waves. *Ocean Engineering*, 96, 125–138.
- [17] Rajendran, S., Fonseca, N., & Guedes Soares, C. (2016). A numerical investigation of the flexible vertical response of an ultra large containership in high seas compared with experiments. *Ocean Engineering*, 122, 76–92.
- [18] Riesner, M., Papanikolaou, A., & Zaraphonitis, G. (2021). A numerical method to compute global resonant vibrations of large ships in waves. *Applied Ocean Research*, 115, 102847.
- [19] Schirrmann, M. L., Collette, M. D., & Gose, J. W. (2022). Data-driven models for vessel motion prediction and the benefits of physics-based information. *Applied Ocean Research*, 120, 102916.
- [20] Schirrmann, M. L., Gose, J. W., & Collette, M. D. (2023). A comparison of physics-informed data-driven modeling architectures for ship motion predictions. *Ocean Engineering*, 286, 115608.
- [21] Senjanović, I., Malenica, Š., & Tomašević, S. (2009). Hydroelasticity of large container ships. *Marine Structures*, 22(2), 287–314.
- [22] Si, H., Lu, Y., Yang, H., Li, Y., Wang, H., & Li, C. (2025). Investigation of higher-order springing of a ship in regular waves. *Marine Structures*, 99, 103697.
- [23] Vijith, P. P., Fonseca, N., & Guedes Soares, C. (2023). Hydroelastic effects on the vertical bending moment of a large ship. *Ocean Engineering*, 285, 115385.
- [24] Wang, H., Duan, W., Chen, J., Li, Y., Yang, H., & Li, C. (2022). A numerical method to compute flexible vertical responses of containerships in regular waves. *Ocean Engineering*, 266, 112828.
- [25] Ye, Y., Wang, H., Duan, W., Chen, J., Li, Y., Yang, H., & Li, C. (2026). Global and structural hydroelastic analysis of a large container ship. *Results in Engineering*, 29, 103672.
- [26] Zhang, Z. F., Wen, Y., Li, C., & Duan, W. (2024). Investigation on whipping characteristics of a container ship in irregular waves using a BEM-Timoshenko beam coupled method. *Ocean Engineering*, 302, 117694.