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RESEARCH ARTICLE

Single-Objective PSA Framework for Longitudinal Girder Scantlings with Full-Ship and Ultimate Strength Verification for a 500-Tonne Catamaran

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ABSTRACT

Hull structures must withstand design loads throughout their expected lifetime. Industry practice often uses a comparative approach, which works for designs similar to proven ships with good service records. However, it can leave some members overly heavy while others barely meet strength criteria, and errors may remain hidden until construction. To prevent such issues at the initial design stage, scantlings should be optimised and reviewed numerically.

To address these limitations in the initial design stage, this study aims to develop and demonstrate a practical numerical framework for optimising hull scantlings by integrating a fully automated single-objective optimisation procedure with direct structural analysis. The optimisation is formulated as a single-objective problem in which the longitudinal girder weight is minimised subject to explicit constraints on yielding, buckling and classification-society scantling limits. The framework is applied to a 500-tonne DWT steel catamaran, in which the longitudinal girders are selected as design variables and the structural responses are evaluated by nonlinear finite-element analyses. The procedure is organised into three stages using finite-element models: a full-ship model to determine global wave-induced responses under design waves derived from North Atlantic wave data at transfer-function maxima; a three-hold model in which the longitudinal girder scantlings are optimised under the governing load cases; and a one-slice model to verify the hull-girder ultimate strength of the optimised midship section. The optimisation applied to the three-hold achieves a 4.53% reduction in their weight, which corresponds to a 3.81% reduction in the total hull structural weight, while satisfying the relevant classification rule requirements. The one-slice ultimate strength assessment confirms that the hull-girder strength remains approximately 10.9% and 13.5% above the KR design requirements although the hogging and sagging ultimate bending capacities decrease by about 6.1% and 5.2%, respectively. These results indicate that the proposed optimisation-based framework can be effectively used as a systematic design procedure to refine rule-based scantlings for small and special-purpose vessels without compromising ultimate strength or global longitudinal structural safety. This study is carried out using the commercial finite-element solver MAESTRO.

Keywords: Structural optimisation, Ultimate strength, Full-ship analysis, Weight reduction, Structural safety, Steel catamaran

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1. Introduction

Unlike monohulls, catamarans are increasingly preferred because they combine wide deck areas with

favourable stability. Their twin-hull arrangement reduces roll motions and improves passenger comfort. Slender demi-hulls lower wave-making resistance at medium to high Froude numbers, and the shallow

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Nomenclature	
B_f	flange breadth
E	elastic modulus
H_w	web height
L_{oa}	length overall
T_f	flange thickness
T_w	web thickness
ρ	density
σ_y	yield stress
ν	Poisson's ratio

draught improves near-shore accessibility. These advantages are driving sustained growth in catamaran adoption across regions and sectors.

Despite these strengths, important structural design challenges remain. Pitch-induced global bending moments increase stresses in the bridge deck and hull-bridge connections, and tunnel slamming can impose severe transient loads. A wide beam can also restrict berthing options and increase construction costs. In practice, such risks are often managed through modifications to the structural layout, local reinforcements, and scantling adjustments. Because the initial design stage is constrained by time and cost, many projects begin with a comparative baseline that reuses a proven structural scheme from a similar vessel within the same ship type.

Comparative design improves efficiency at the concept stage and is consistent with class rules and shipyard practice. However, its direct transfer becomes unreliable for catamarans when principal dimensions or operating conditions deviate from the reference vessel. Increased hull spacing and bridge-deck span shift the neutral axis and reduce effective section modulus, thereby elevating pitch-induced bending stresses. A wider beam enhances exposure to asymmetric wave loading, which increases torsional and warping demands and modifies natural frequencies. These effects alter global load paths, redistribute shear flow, and change joint forces at hull-bridge connections, so that structural behaviour can depart significantly from that of the precedent. Direct one-to-one reuse of scantlings can therefore leave some members unnecessarily heavy while others barely satisfy strength criteria, and latent weaknesses may not be identified until late in the design or construction process. It is thus appropriate to treat comparative design only as a starting point and to supplement it at an early stage with optimisation of key scantlings and structured strength checks under realistic sea states and practical build constraints, in order to secure consistent strength, durability, weight, and lifecycle performance.

This study proposes a practical numerical framework that integrates fully automated single-objective

optimisation with direct structural analysis to improve the scantling design of a steel catamaran. The objective is to reduce structural weight while maintaining rule compliance and adequate safety margins throughout the service life. The framework is demonstrated for a 500-tonne DWT steel catamaran in which the longitudinal girders are selected as design variables, and structural performance is evaluated by nonlinear finite-element (FE) analyses using the commercial solver MAESTRO. Three FE models are introduced: a full-ship model to capture global wave-induced responses, a three-hold model in which the longitudinal girder scantlings are optimised under the governing load cases, and a one-slice model to verify the hull-girder ultimate strength of the optimised midship section. Design waves are selected from North Atlantic wave data at response-amplitude-operator maxima. As the present study focuses on the structural responses under the selected design waves, the detailed derivation procedure of these design waves is not described herein. Within this framework, the optimisation problem is formulated explicitly to balance structural efficiency and rule compliance, as described below.

This study proposes a practical and implementable numerical framework that integrates fully automated single-objective optimisation with direct structural analysis to improve the scantling design of a steel catamaran. These constraints are treated as mandatory feasibility conditions throughout the optimisation process, ensuring that all candidate designs remain structurally compliant while weight efficiency is improved.

Although the optimisation variables are limited to longitudinal girder scantlings, the proposed framework explicitly accounts for the catamaran-specific transverse bending behaviour through full-ship analyses under wave-induced transverse bending moments. These global responses govern the load environment imposed on the three-hold optimisation model, thereby ensuring that the optimisation of longitudinal members is performed within a realistic transverse load context representative of catamaran structural behaviour.

2. Literature review

It is widely recognised that the structural design of ship hulls has been dominated by rule-based and comparative approaches established by classification societies. These rules provide prescriptive formulae for primary scantlings based on empirical calibration and accumulated experience, and they are particularly effective for conventional monohull cargo ships

(IACS, 2014). For small to medium-sized vessels and high-speed craft, including catamarans, designers frequently adopt a comparative method in which scantlings are selected by analogy with existing approved vessels of similar type. This practice offers simplicity and reduced design time; however, it tends to retain hidden conservatism or local insufficiencies and provides limited transparency regarding the actual utilisation of structural capacity under realistic load combinations. As hull forms, material arrangements, and operational profiles become more diverse, there is increasing concern that purely rule-based or comparative designs may not adequately reflect the true load-carrying behaviour of unconventional configurations such as steel catamarans.

In response, extensive research has been devoted to direct strength assessment methods based on FE analysis and ultimate limit state (ULS) concepts. Paik and Thayamballi (2003) and Paik (2018) systematised ULS-based assessment procedures for plated and stiffened structures, demonstrating that nonlinear FE analysis can capture the progressive collapse behaviour of stiffened panels and hull girders under combined loading and can be used in parallel with or in support of prescriptive rules. Subsequent studies on panel and hull-girder ultimate strength further established procedures for checking yielding, buckling and collapse under still water and wave-induced loads (Paik & Kim, 2002; Hughes & Paik, 2010). These ULS-based direct assessment approaches have been applied mainly to large tankers, bulk carriers and container ships, particularly in connection with longitudinal strength standards such as IACS UR S11 and UR S11A (IACS, 2014, 2015). However, there are relatively few documented applications in which such direct assessments are embedded systematically in the early-stage scantling design of smaller specialised vessels, including steel catamarans, within a coherent and repeatable workflow. For catamarans in particular, several studies have analysed global and local responses or ultimate strength using finite element models (Heggelund et al., 2000; Wang et al., 2006; Xu et al., 2019; Kim et al., 2020; Julianto et al., 2020). However, these works typically address specific loading conditions or configurations and are not embedded within an integrated optimisation-based scantling procedure that combines full-ship analysis and hull-girder ULS verification as a coherent early-stage design framework.

Parallel to the development of direct strength methods, structural optimisation techniques have been explored as means to achieve more rational scantling configurations. Gradient-based algorithms, evolutionary strategies and other metaheuristics have been used to minimise structural weight or fabrica-

tion cost under constraints derived from classification rules, stress limits and buckling criteria. Among these approaches, Pareto-type simulated annealing and related metaheuristics have been proposed as flexible search schemes for discrete scantling sets and nonlinear responses (Singh et al., 2010). In the naval architecture field, Kim and Paik (2017) developed a ULS-based multi-objective optimum design technology for hull structural scantlings of merchant cargo ships, showing that metaheuristic search can identify alternative designs beyond conventional rule-based solutions by considering weight, cost and ULS indices simultaneously. Other studies (Ma et al., 2013; Jang et al., 2019; Koni, 2022; Abedin et al., 2024) have applied multi-objective or heuristic optimisation to stiffened panels, local regions or specific offshore structures, confirming the potential of such algorithms but also highlighting their computational cost and implementation complexity when fully coupled with nonlinear analyses for practical design.

Recent works therefore indicate a need for practical frameworks that embed optimisation directly into established design procedures whereas remaining compatible with class rules and existing FE tools. In this context, single-objective formulations, in which structural weight is minimised subject to explicit constraints on stress, buckling and rule compliance, have emerged as attractive options. These formulations preserve conceptual consistency with the ULS-based design philosophy (Paik & Thayamballi, 2003; Paik, 2018), yet avoid the complexity of explicit Pareto ranking and are easier to implement within commercial analysis environments. Despite this, there remains a noticeable gap in the literature regarding applications where (i) a single-objective optimisation of longitudinal girders is conducted for a real vessel based on discrete, rule-consistent scantling sets, (ii) the resulting scantlings are propagated to a full-ship FE model to confirm global behaviour and hotspot responses, and (iii) the final configuration is verified through an independent ULS assessment of the critical hull-girder section within a unified procedure.

The present study addresses this gap by proposing and demonstrating an integrated, single-objective optimisation framework for the longitudinal girders of a 500-tonne steel catamaran. The procedure links three complementary FE models—a full-ship model for global response, a three-hold model for optimisation under governing bending conditions, and a one-slice model for ultimate strength evaluation—within a workflow aligned with classification requirements. In doing so, it is positioned between purely rule-based comparative practice and more complex multi-objective research formulations, and it aims to provide a realistic and implementable decision-

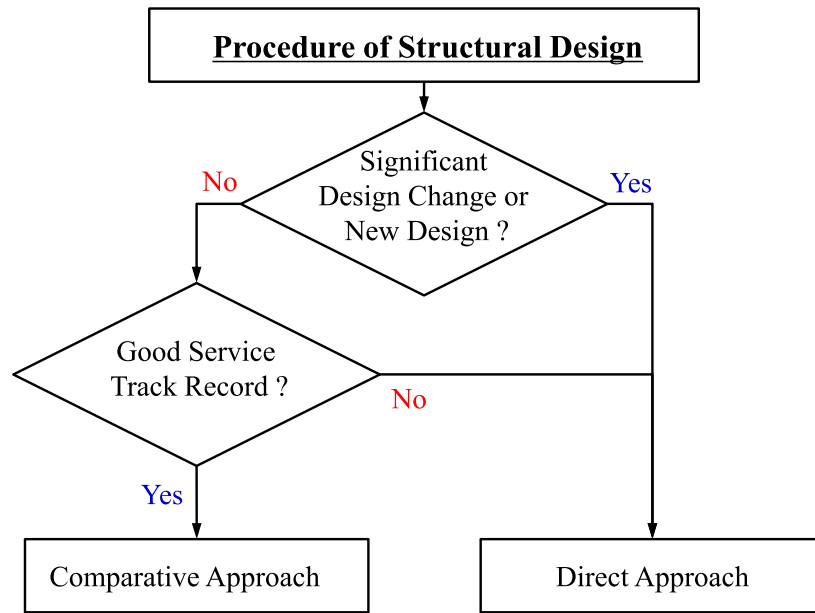


Fig. 1. Procedure of structural design in general.

support tool for practitioners involved in the direct strength design of steel catamaran hull structures.

3. Proposed design procedure

3.1. General procedure

It is critical in ship design to ensure the structural safety of the hull under all operating sea states. At a minimum, this is commonly secured by designing in accordance with established standards, regulations, and the rules of classification societies, which have evolved largely from accumulated experience. These rule-based approaches are simplified and formalised to facilitate practical use in determining the scantlings of principal members and arranging the primary structural layout

In general, there are two approaches for structural design: the comparative method and the direct method, as shown in Fig. 1.

The former is a common approach for designing hull scantlings based on a previous ship design. It can provide a sound basis for standard or conventional designs that is similar to a previous proven design with a good track record. However, it may not be reliable when a major design parameter changes significantly.

Under these conditions, the latter is preferred, particularly for a novel design that goes beyond the proven design. It is based on finite-element modelling to secure hull structural safety beyond what existing standards, regulations, or class rules explicitly cover. It is now common practice to evaluate, as accurately

as practicable, the full set of loads arising from the actual operating sea states and to apply these loads to the structural safety assessment, thereby achieving a more realistic analysis.

Even with these two design approaches, there are still some structural members that are overly heavy while others barely meet the strength criteria, and errors may remain hidden until construction. These tendencies are even worse in the design of small special ships. Therefore, to prevent such issues at the initial design stage of these vessels, scantlings should be optimised and reviewed numerically.

Accordingly, the present study proposes a new procedure (Fig. 2) that adds an explicit optimisation stage to the conventional direct structural analysis. The procedure first verifies safety by direct analysis under the load cases. It then runs an optimisation loop that adjusts scantlings within rule constraints to meet strength and buckling criteria with minimum weight. The result is a design that remains rule-compliant and structurally safe, while improving structural efficiency and design transparency.

As indicated in Figs. 1 and 2, the proposed framework extends the conventional direct approach by inserting an explicit scantling optimisation stage between the initial direct strength assessment and the final verification analyses.

3.2. Optimisation-based direct analysis procedure

3.2.1. Extreme design wave

Primary member scantlings must be set against the most severe loading condition that a ship may

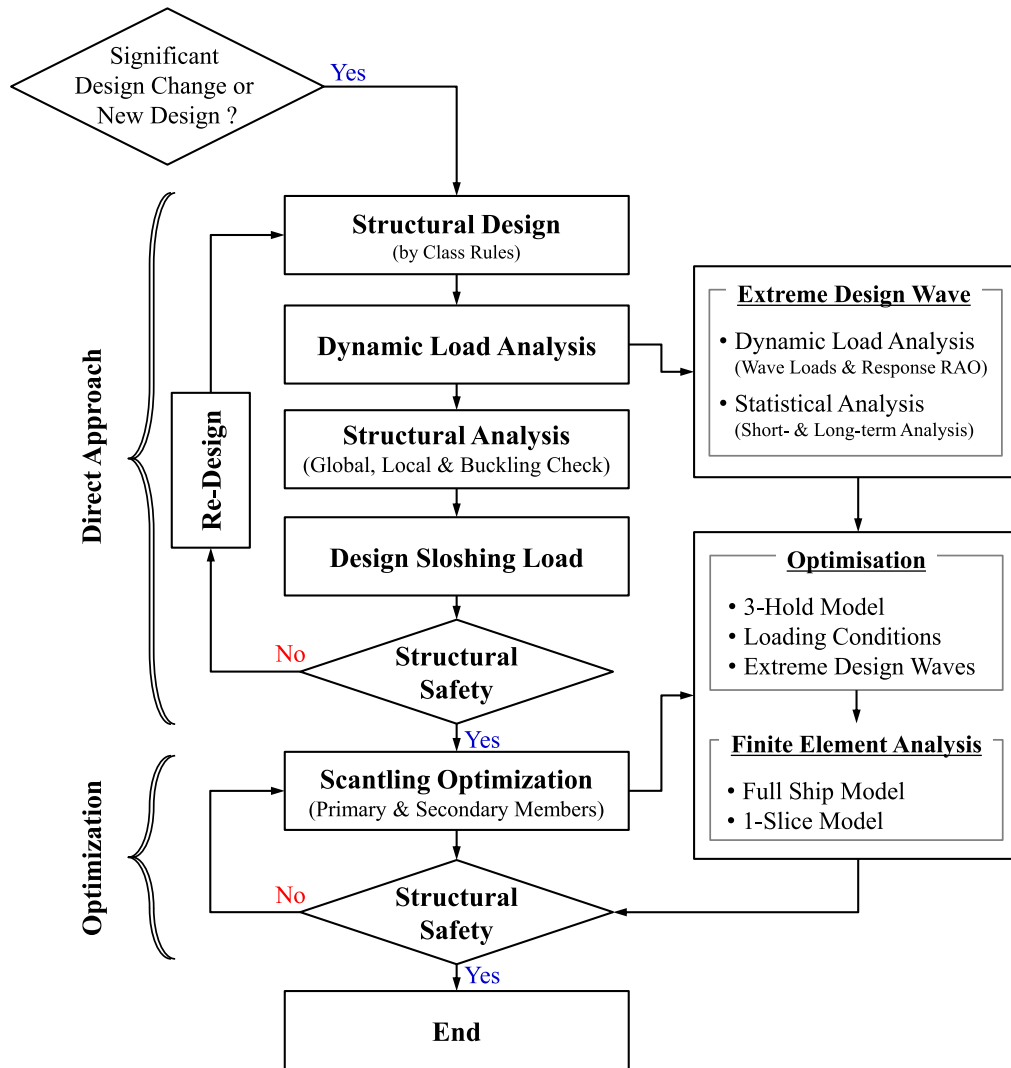


Fig. 2. Proposed design procedure for scantling optimisation.

experience during its lifetime. This condition is determined using probabilistic–statistical methods. Under the common assumption that the lifetime irregular sea can be represented as a superposition of all possible regular (sinusoidal) waves, one first computes structural responses to regular waves and then performs statistical analysis based on a wave spectrum (short-term sea) and long-term wave data / scatter diagrams to obtain the most probable extreme value.

For the location of interest, compute loads for all regular waves, estimate the extreme load by statistical analysis, and select the single equivalent regular wave—the design wave—that produces that extreme. Three-dimensional structural analysis under this wave then yields the stress distribution under the extreme load, which is checked against allowable stress for final acceptance. Because analysis is required only for a few governing load cases and their design waves, time and effort are reduced.

The present study adopts design waves determined by such a procedure in a separate analysis; here, attention is focused on the structural responses under the selected design waves rather than on the detailed derivation steps.

3.2.2. Scantling optimisation

In this study, the optimisation is applied to the longitudinal girders, which are selected as the primary design variables, while other members remain as in the rule-based baseline design. More generally, such a framework can be extended to treat the scantlings of longitudinal plate panels, longitudinal stiffeners and primary support members, as well as selected spacing parameters, as design variables within prescribed practical limits. As the spacing of major supporting members is usually constrained by cargo arrangement and construction requirements, such extended applications would mainly target plate thicknesses and the

sizes of small or highly stressed stiffeners and girders. These variables are adjusted in a single-objective framework in which structural weight is minimised while at least maintaining, or where possible increasing, structural safety within the limits prescribed by the classification rules.

The optimisation is implemented using a heuristic Pareto-based simulated annealing algorithm in MAESTRO, which is employed here as a constrained single-objective search scheme. For each candidate design, the three-hold model is re-analysed, and the resulting strength, buckling and weight measures are used to guide the search towards designs that minimise weight while satisfying all prescribed criteria.

Upon convergence, the optimised scantlings are verified by finite element analyses using both a full-ship model and a one-slice model representing the critical transverse cross-section(s) under the governing load combinations. Global and local responses are checked against the prescribed acceptance criteria. If all checks are satisfied with adequate margins, the optimised scantlings are accepted as ensuring structural integrity under the specified design loads; otherwise, the optimisation–analysis cycle is repeated with adjusted constraints or design variables until a compliant solution is obtained.

The full-ship finite element model is employed to establish the global load environment and to verify the final structural response, whereas the three-hold model is adopted for the optimisation loop in order to achieve computational efficiency while preserving sufficient fidelity in representing the governing vertical and transverse bending boundary conditions. The three-hold model inherits its loading conditions directly from the full-ship analysis, ensuring consistency between global response and local optimisation.

4. Finite element modelling

In this chapter, an applied example was represented according to the proposed analysis procedure.

4.1. Target vessel

The target vessel, a 500-tonne steel catamaran, was illustrated in Fig. 3. The principal dimensions are summarized in Table 1. It is considered that various vehicle loading conditions for the target vessel are applied, including passenger cars, cargo trucks, large buses and heavy trucks. A ferry with a breadth of 19.8m is selected as the final design, and the optimal vehicle arrangement on the car deck is determined accordingly.

Table 1. Principal dimensions.

L_{oa} (m)	Breadth (m)	Draft (m)	Speed (kts)
66.53	19.80	2.55	17.0

4.2. Mesh models

In this study, finite element analyses are carried out for three models. Fig. 4 describes the three FE mesh models for the present study. The primary structural members in all three models are represented by four-node quadrilateral and three-node triangular shell elements, while local stiffeners and girders are modelled using equivalent shell strips consistent with MAESTRO practice.

4.2.1. Full-ship model

The full-ship model is used to evaluate hydrostatic and hydrodynamic loads under the governing full-load condition and the associated design waves specified in Table 3, which represent the most probable extreme vertical and transverse bending responses for the selected trading route. The hydrostatic pressure is determined such that buoyancy and weight are in equilibrium and no net unbalanced force is generated. In this study, wave-induced vertical and transverse bending moments at midship, as defined in Table 3, are considered as the governing global loading conditions.

4.2.2. Three-hold model

In the three-hold finite element model, the structural strength is evaluated under the governing sagging and hogging vertical bending moments (122.2 and -163 MNm), which are determined in accordance with the Korean Register (KR, 2024) wave load criteria and are consistent with the design-wave-based global analysis. This model is employed as the basis for the scantling optimisation.

4.2.3. One-slice model

To evaluate and compare the variation in ultimate strength of the steel catamaran resulting from the optimisation, a nonlinear structural analysis is performed using a one-frame slice at the midship region representing the critical transverse section.

The full-ship model consists of 36,823 nodes and 151,609 elements, the three-hold model comprises 6,661 nodes and 21,600 elements, and the one-slice model comprises 642 nodes and 1,472 elements. In all models, only the principal structural members of the steel catamaran are represented, while outfit items such as seats, stairways and other minor fittings are excluded from the modelling.

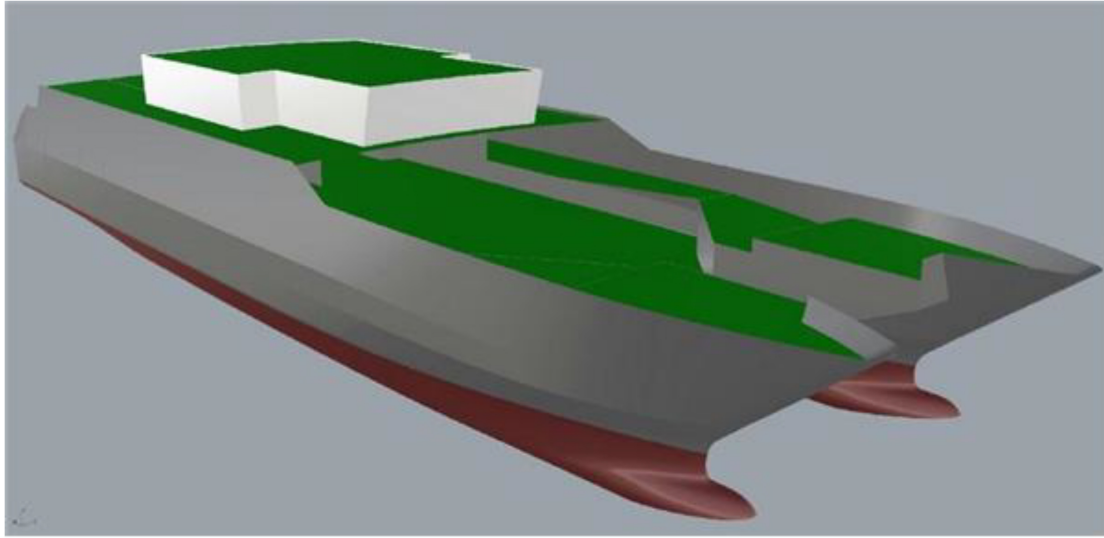


Fig. 3. Target vessel: 500-tonne steel catamaran.

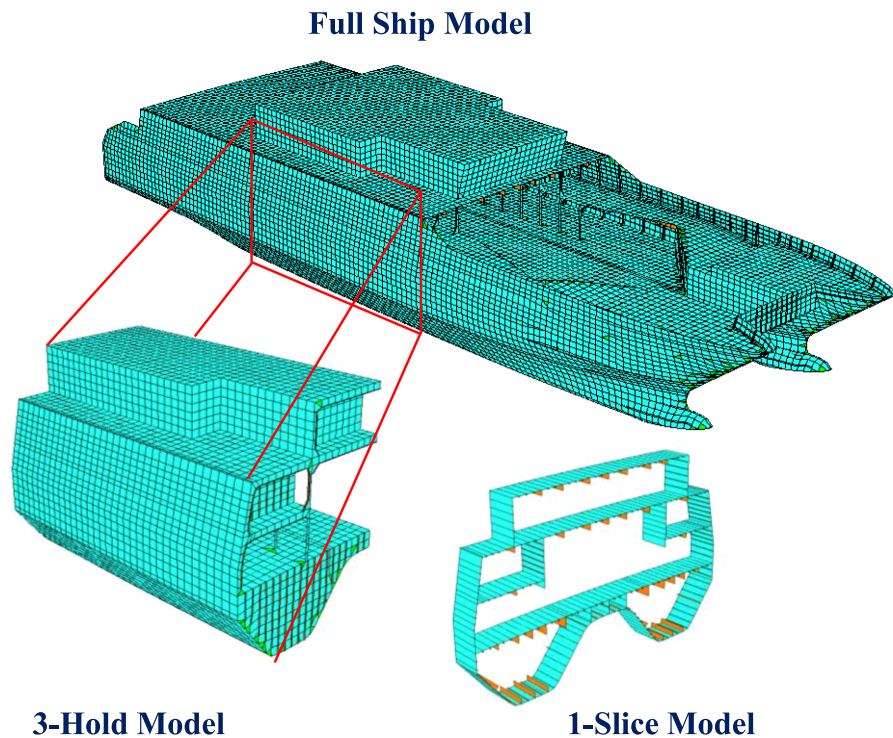


Fig. 4. Finite element models: full-ship, three-hold and one-slice.

4.3. Boundary conditions and loading

In the present study, three boundary points (A-C) are introduced, as shown in Fig. 5. For full-ship mesh model, three nodal points were selected for the boundaries. The details of them were summarised in Table 2.

The loading conditions applied in the full-ship analysis are defined with the same draft for all cases, as follows:

- Full-load still-water condition
- Wave-induced vertical bending moments in sagging and hogging
- Wave-induced transverse bending moments in sagging and hogging

For the three-hold model, the structural analysis is performed under the following wave-induced vertical bending moments:

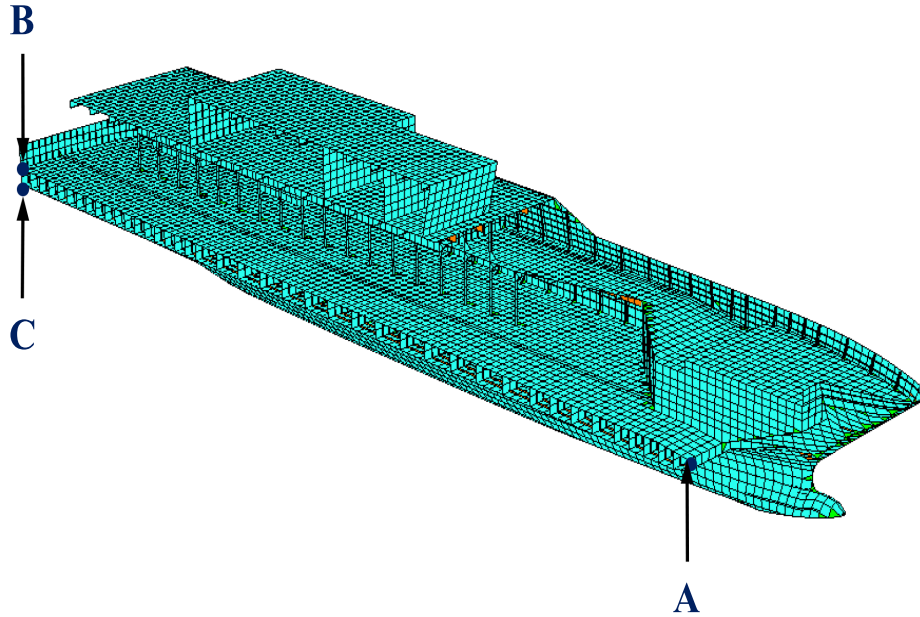


Fig. 5. Boundary conditions of the full-ship mesh model.

Table 2. Applied boundary conditions for the full-ship mesh model.

Points	X	Y	Z
A	Free	Fix	Fix
B	Free	Fix	Free
C	Fix	Fix	Fix

- Sagging: 122.2 MNm
- Hogging: –163 MNm

For the one-slice model, the ultimate strength of the midship transverse section is evaluated by applying displacement-controlled loading to both sides of the section until the maximum load-carrying capacity is reached.

4.4. Weight distribution

Using the generated full-ship mesh model, the distribution of weights acting on the hull was obtained by applying the light weight and the specified distributed loads. For calculation of light weight, mild steel was applied (yield stress $\sigma_y=235\text{MPa}$, elastic modulus $E=204\text{GPa}$, density $\rho=7850\text{kg/m}^3$, Poisson's ratio $\nu=0.3$)

Figs. 6 and 7 show the weight and buoyancy distribution of the full-ship model in full load condition. It is noted that the maximum weight occurs 20m away from stern. The maximum buoyancy appears between 15-20m away from the stern.

In particular, the internal structural responses under the full-load condition are examined in Fig. 8.

These results are used to verify that a physically consistent longitudinal and transverse load environment has been established prior to detailed strength assessment and optimisation.

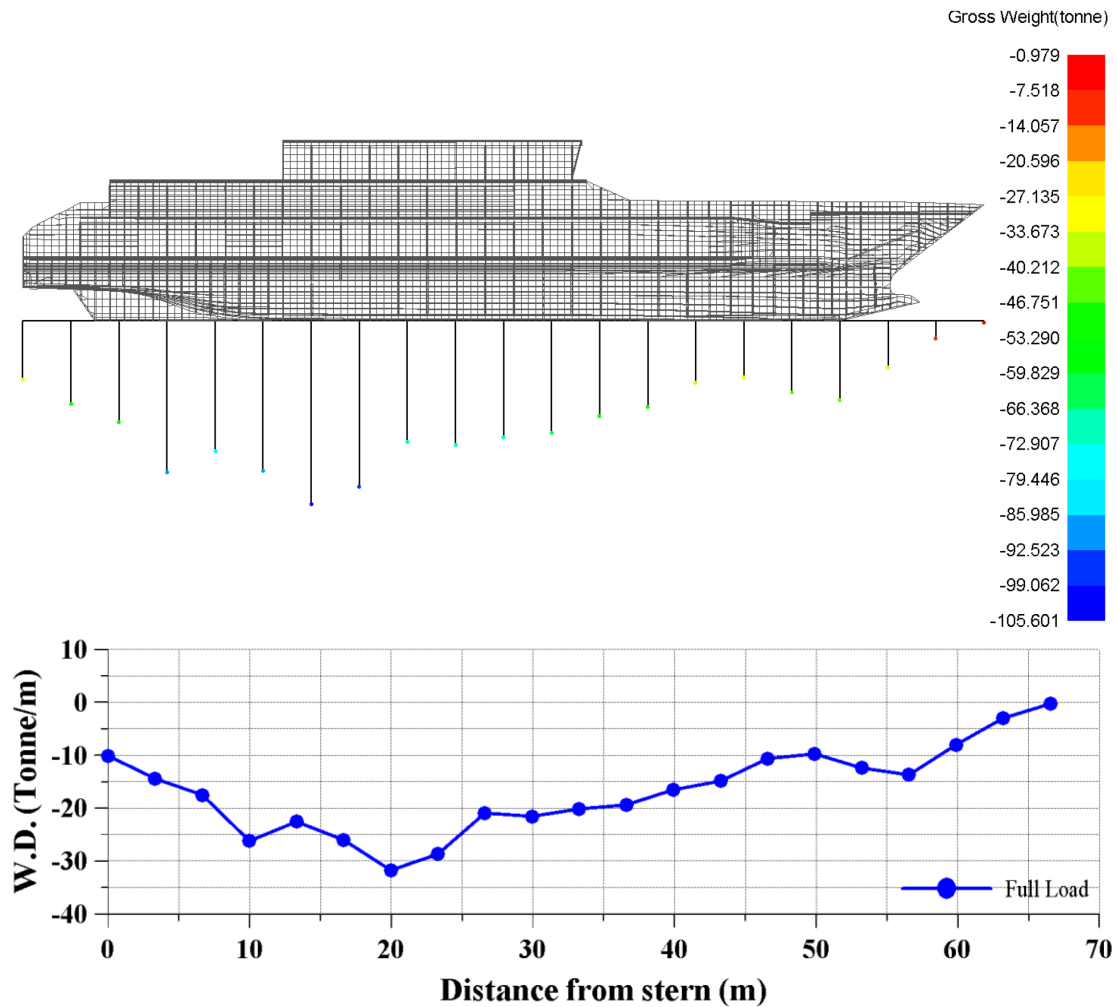
In Fig. 8(a), the vertical shear force varies smoothly along the length, with negative values developing in the midship region and recovering towards the bow. The zero-crossings indicate locations where the cumulative weight and buoyancy are in local equilibrium. The absence of abrupt changes implies that the assumed weight–buoyancy distribution does not introduce unrealistic local load concentrations, and that the longitudinal load balance is reasonable.

Fig. 8(b) shows the vertical bending moment distribution, which exhibits a typical sagging-dominant pattern, reaching its maximum magnitude in the midship region and decreasing towards the ends. This confirms that the central part of the catamaran is subjected to the most severe global vertical bending, consistent with conventional ship-type behaviour, and provides the governing condition for the longitudinal strength assessment and subsequent scantling optimisation.

The transverse bending moment distribution in Fig. 8(c), plotted with respect to the distance from the centreline, indicates significant transverse bending across the bridge deck between the twin hulls. Positive moments occur near the centreline, while negative moments develop towards the outer sides, reflecting the load transfer mechanism between the demi-hulls and the cross-deck structure. The magnitude and shape of this curve highlight that the bridge

Table 3. Full-load conditions and design waves.

Loading Conditions		Design Waves					
		Draft [m]	Length [m]	Period [s]	Height [m]	Phase Angle [°]	Direction [°]
Still Water		2.55	–	–	–	–	–
Vertical Bending Moment	Sagging	0.29	56.19	6	3.88	–17.24	180
	Hogging	2.07	56.19	6	3.88	–197.24	180
Transverse Bending Moment	Sagging	2.69	39.02	5	2.95	78.48	90
	Hogging	2.82	39.02	5	2.95	–101.52	90

**Fig. 6.** Weight distribution in the full load condition.

deck, transverse frames and cross-deck girders must be designed to resist transverse bending as one of the key governing actions.

In Fig. 8(d), the horizontal bending moment along the ship length remains comparatively small and varies smoothly, indicating that lateral global bending is not a dominant design driver for this vessel under the considered loading condition. Consequently, the structural design is primarily governed by the vertical bending and the transverse bending associated

with the catamaran configuration, while the horizontal bending moment is confirmed to be of secondary importance.

Therefore, these shear force and bending moment distributions demonstrate that the adopted weight and buoyancy model produces a consistent and realistic global load environment for the 500-tonne steel catamaran and provides a clear basis for the subsequent full-ship, three-hold and one-slice finite element analyses.

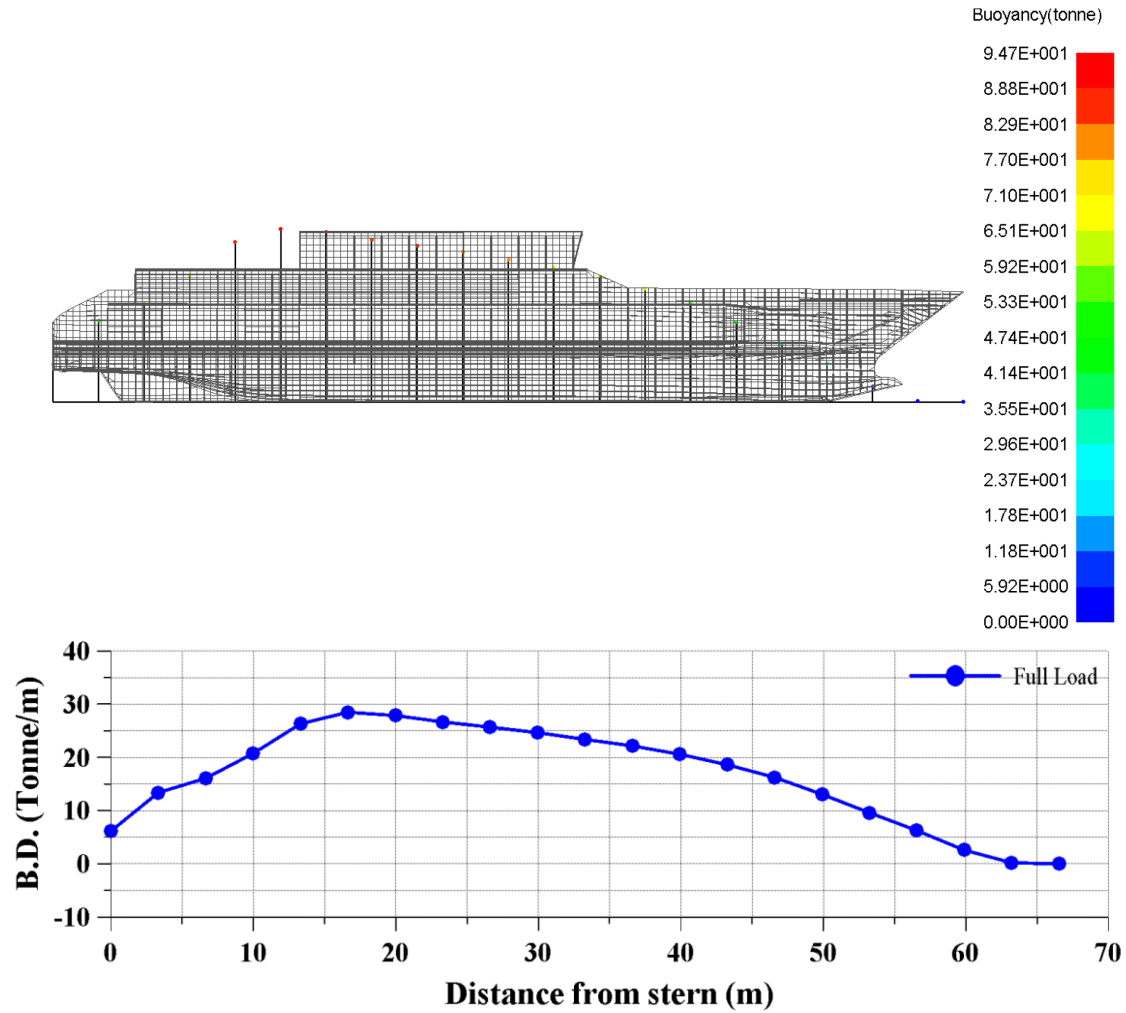


Fig. 7. Buoyancy distribution in the full load condition.

5. Finite element results

5.1. Optimisation results

The optimisation technique applied to the hull structure is the Pareto simulated annealing method implemented in MAESTRO. In the present study, only longitudinal girders were treated as design variables; plating and transverse members remain as in the rule-based baseline.

The design variables are constrained as follows:

- web height, H_w , $300 \leq H_w \leq 750$ mm,
- web thickness, T_w , $8 \leq T_w \leq 12$ mm,
- flange breadth, B_f , $100 \leq B_f \leq 200$ mm,
- flange thickness, T_f , $8 \leq T_f \leq 14$ mm.

There are 17 types of girders in the target vessel and their initial dimensions and their optimisation results are listed in the Table 4. In this optimised configuration, the resulting scantlings provide a mod-

est but meaningful reduction in hull girder weight while satisfying all prescribed strength criteria. For the three-hold cargo model, the steel weight decreases from 121.3 tonne in the initial design to 115.8 tonne after optimisation, corresponding to a reduction of 4.53%. When the optimised scantlings are consistently extended to the full ship model, the total hull weight is reduced from 695.7 tonne to 669.2 tonne, i.e. by 3.81%. These results confirm that the conservative nature of the initial scantlings can be relaxed towards the lower bounds of the admissible design space without compromising rule compliance, thereby achieving a more weight-efficient structural configuration.

In Fig. 9, the global stress distributions of the three-hold FE model under the governing sagging and hogging bending moments specified in Table 3 are compared between the original and optimised scantlings. In the original configuration, relatively high von Mises stresses are observed in the upper deck

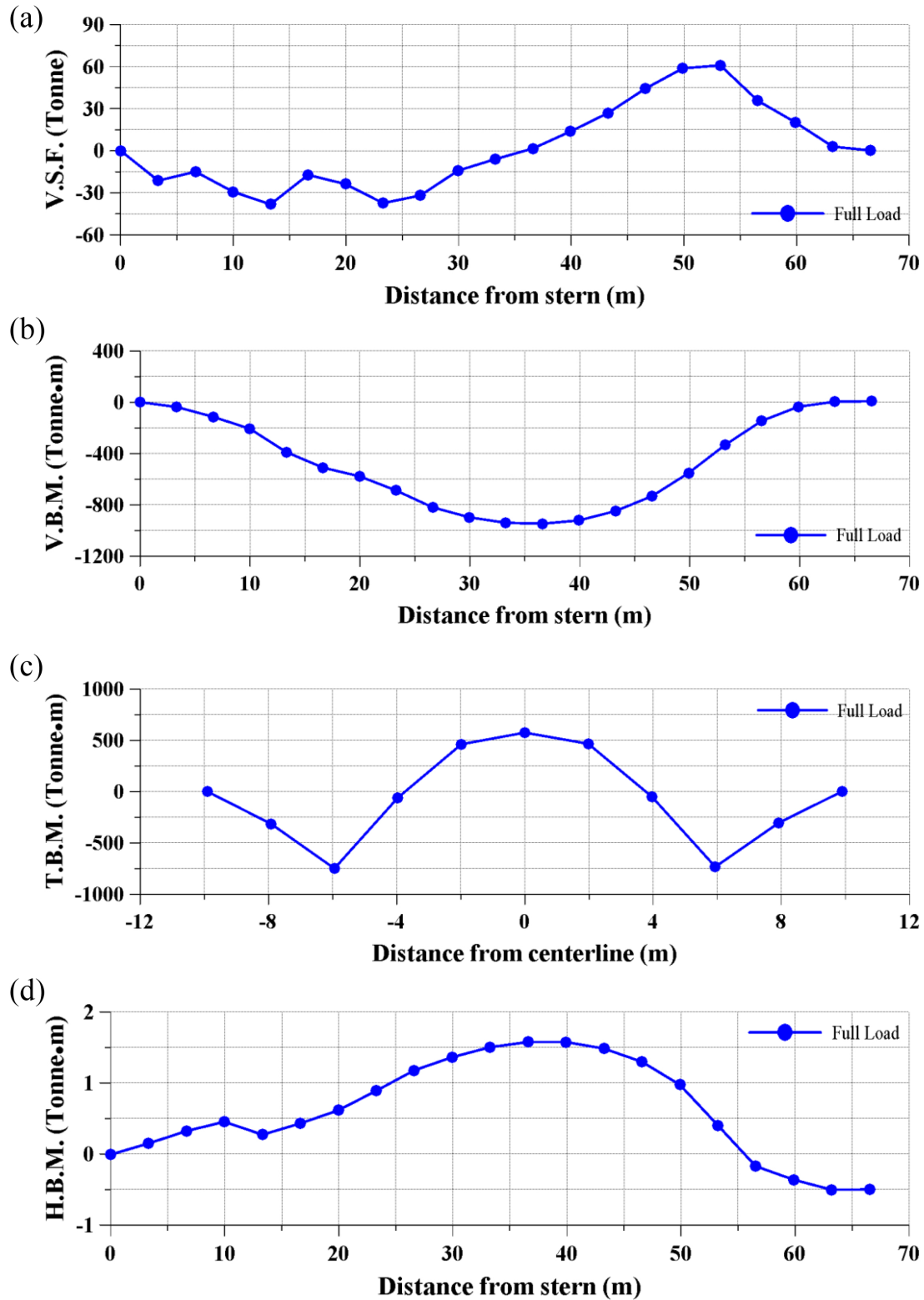


Fig. 8. Internal structural response under the full load condition.

Table 4. Comparison of girder section dimensions before and after optimisation.

Initial ($H_w \times T_w \times B_f \times T_f$)	Optimised ($H_w \times T_w \times B_f \times T_f$)
344.0×8.0×150.0×12.0	300.0×8.0×100.0×8.0
465.0×8.0×150.0×12.0	
624.0×8.0×150.0×12.0	
733.0×8.0×150.0×12.0	
547.0×8.0×150.0×12.0	
300.0×8.0×300.0×12.0	
350.0×8.0×300.0×12.0	
350.0×10.0×300.0×12.0	
312.0×8.0×150.0×10.0	
331.0×8.0×150.0×10.0	300.0×8.0×106.0×8.0
347.0×8.0×150.0×10.0	300.0×8.0×160.0×8.0
350.0×8.0×150.0×10.0	300.0×8.0×100.0×8.0
324.0×8.0×150.0×10.0	
381.0×8.0×150.0×10.0	
397.0×8.0×150.0×10.0	
400.0×8.0×150.0×10.0	
324.0×8.0×150.0×10.0	

longitudinal and around the opening corners, forming localised hot spots under both sagging and hogging conditions.

After applying the proposed optimisation, the stress fields become more uniform and the peak von Mises stresses are slightly reduced for both sagging and hogging load cases. High-stress regions at the deck and longitudinal girder connections are mitigated, and the overall stress levels in the primary longitudinal members remain below the allowable limit with similar or slightly reduced peak values while the global deformation pattern remains essentially unchanged. This demonstrates that the optimised longitudinal girder scantlings not only achieve weight reduction but also improve the structural efficiency by alleviating local stress concentrations, without introducing any adverse effect on the global strength response.

In Fig. 10, the von Mises stress distributions on the 1st, 2nd and 3rd decks are compared between the original and optimised scantlings. The comparison shows that, with the proposed single-objective optimisation, all decks retain acceptable stress levels, and in several regions the stress field becomes more uniform, demonstrating that the achieved weight reduction is obtained without compromising deck structural integrity.

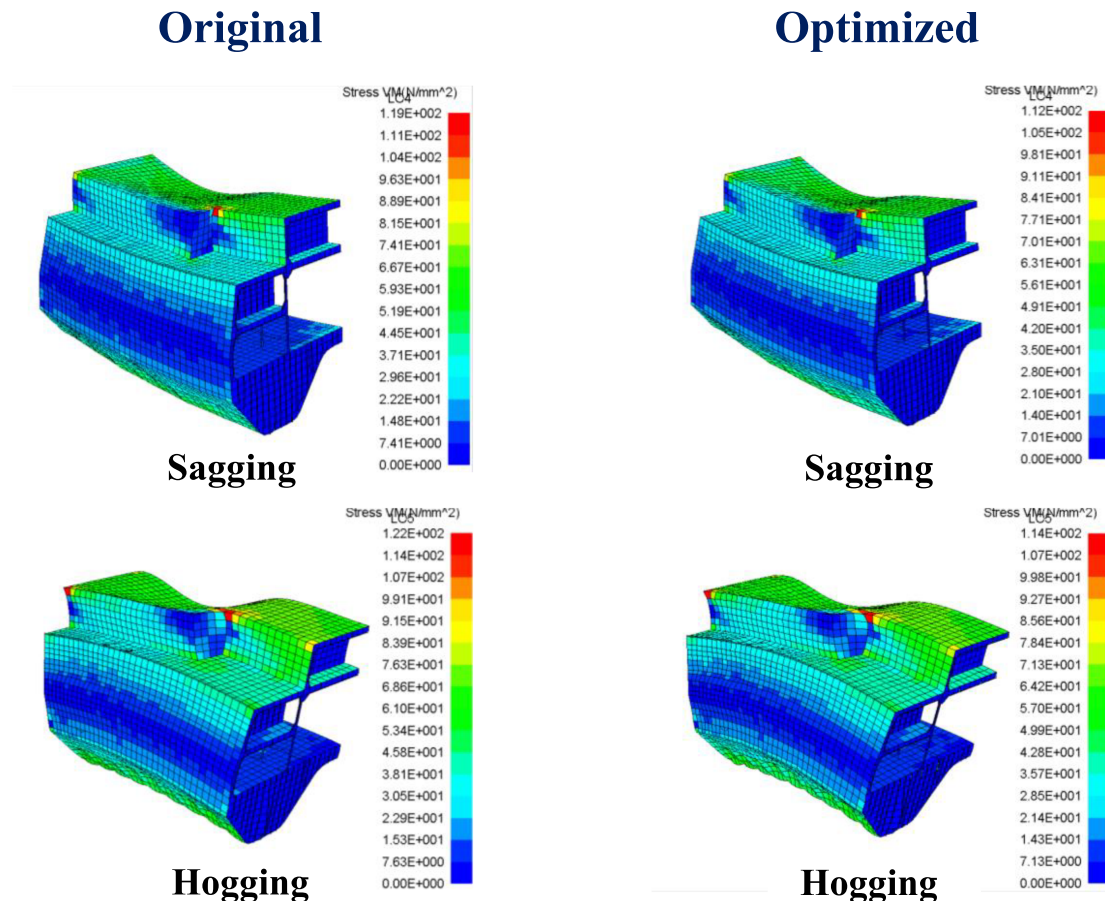


Fig. 9. Comparison of von Mises stress distribution for three-hold FE model under the sagging and hogging bending moment.

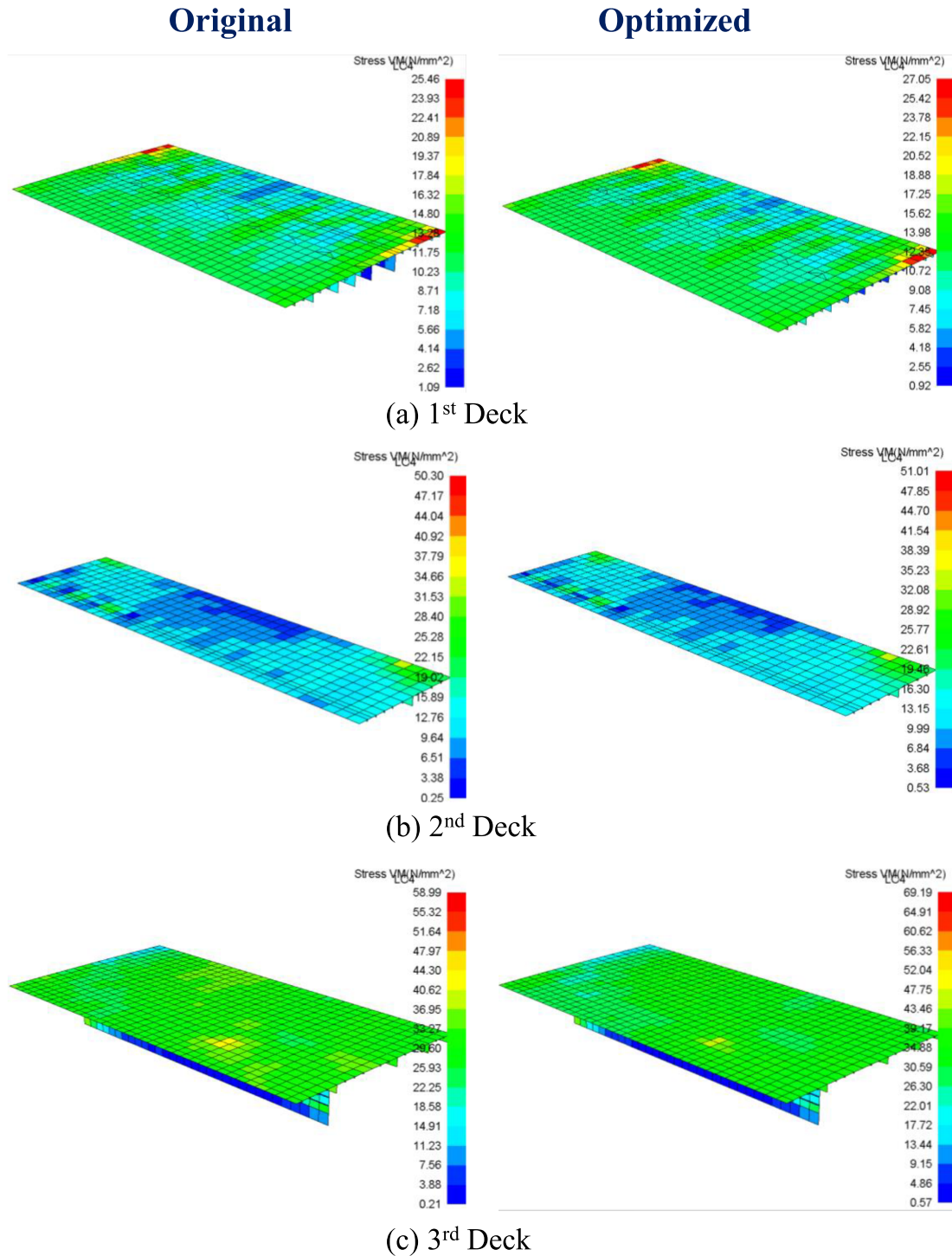


Fig. 10. Comparison of von Mises stress distribution for three-hold FE model under the sagging bending moment: (a) 1st deck, (b) 2nd deck, (c) 3rd deck.

In Fig. 11, the von Mises stress distributions of the three-hold FE model under the rule-based hogging bending moment are compared between the original and optimised scantlings for (a) the 4th deck, (b) the hull centre region, and (c) the hull side shell.

In both the original and optimised configurations shown in Fig. 11(a), higher stresses are confined to the regions adjacent to the openings and the side shell, while the remaining deck area remains in a low-to-moderate stress range. After optimisation, the

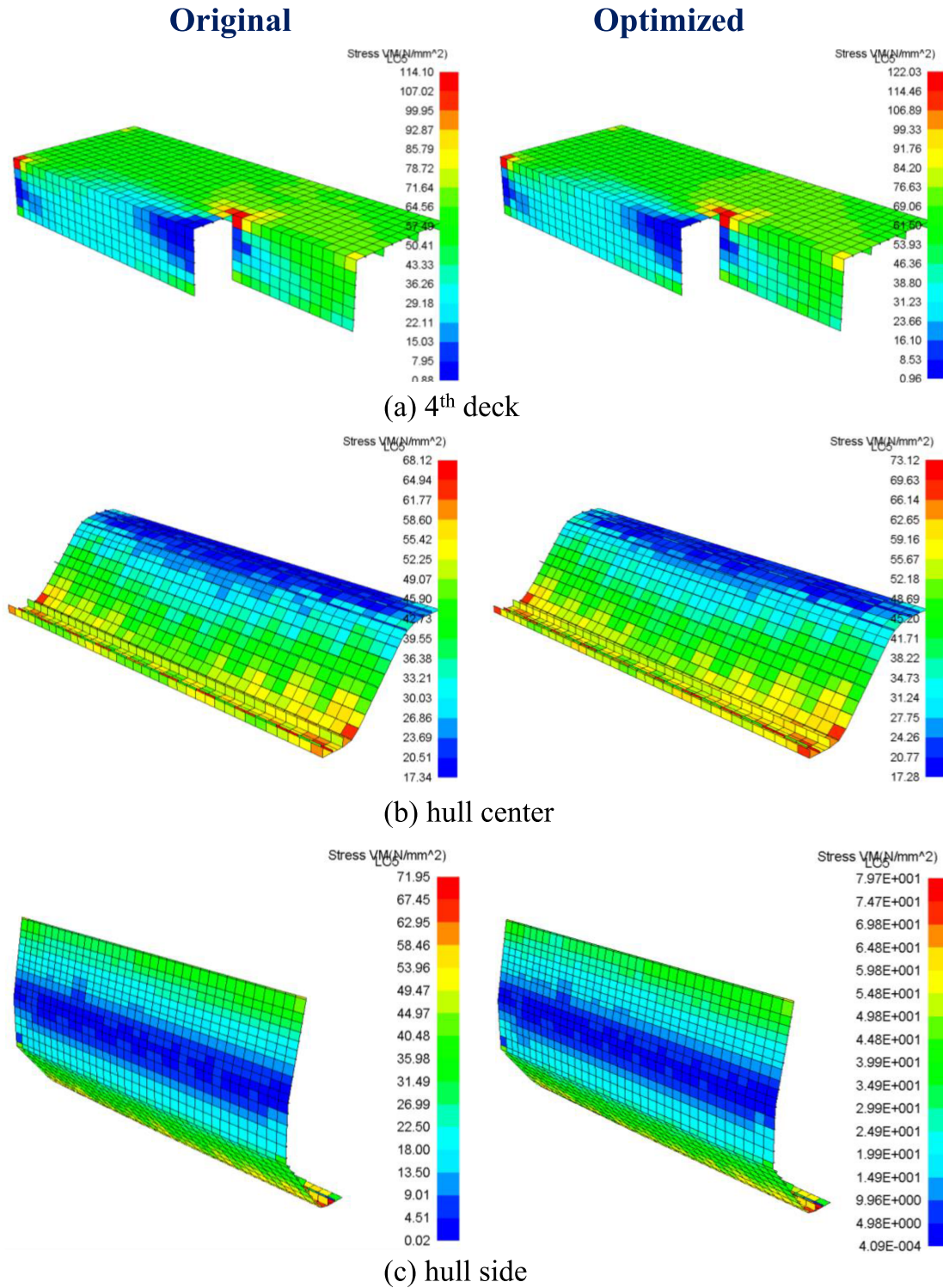


Fig. 11. Comparison of von Mises stress distribution for three-hold FE model under the rule-based hogging bending moment: (a) 4th deck, (b) hull centre, (c) hull side.

overall stress pattern is essentially unchanged; local peak stresses vary only marginally and remain within the allowable limit. This indicates that the weight reduction of the longitudinal girders does not impair

the load-carrying behaviour or safety of the 4th deck, and no new critical hot spots are introduced.

For the hull centre region illustrated in Fig. 11(b), including the connections between longitudinals,

decks and side structure, the stress distributions before and after optimisation exhibit similar smooth gradients with only limited localised peaks. The optimised scantlings result in stress levels and band shapes comparable to the original design, without any excessive expansion of high-stress zones. This confirms that the optimised configuration maintains adequate global stiffness and strength in the central part of the hull under hogging conditions.

Along the side shell shown in Fig. 11(c), the characteristic tension–compression band induced by hogging is observed in both cases, with maximum stresses remaining within the permissible range. After optimisation, the stress pattern is preserved and the stress levels are similar or slightly more uniform in some regions. There is no evidence of increased stress concentration or reduced margin against buckling.

Therefore, the comparisons for the 4th deck, hull centre and hull side demonstrate that the proposed single-objective PSA-based optimisation achieves longitudinal girder weight reduction without degrading the global or local strength performance of the hull, as all critical regions retain sufficient safety margins under the hogging design load.

Fig. 12 compares the von Mises stress distributions of the transverse frames in the three-hold FE model under the rule-based hogging bending moment, before and after optimisation, for (a) between bottom and 1st deck, (b) between 1st and 2nd deck, (c) between 2nd and 3rd deck, and (d) between 3rd and 4th deck.

For the transverse frames between the bottom and 1st deck, both the original and optimised configurations show higher stresses mainly in the centre regions, while the overall stress level remains within the allowable range. After optimisation, the stress pattern is essentially preserved, and although some local peaks change slightly, no new critical hot spots appear. This indicates that the weight reduction of the longitudinal girders does not adversely affect the structural behaviour of the lower transverse framing.

Between the 1st and 2nd decks, band-shaped stress regions occur along the upper parts of the frames and deck connections in both cases. The optimised scantlings lead to stress levels and distributions similar to those of the original design, with only minor increases in some members that still remain below the allowable limit. This confirms that the load-carrying capacity of the transverse system in this region is maintained.

For the transverse frames between the 2nd and 3rd decks, the original design exhibits somewhat higher stresses at selected transverse girders and longitudinal–frame intersections. In the optimised case, certain upper members experience slightly increased stresses, but the overall pattern remains

comparable and all stresses are within acceptable limits. The optimisation thus causes some redistribution without compromising structural safety.

Between the 3rd and 4th decks, both designs are dominated by low stress levels, with only small localised peaks. The optimised scantlings do not introduce any noticeable increase in stress concentration, and sufficient margins are preserved.

Therefore, the comparison demonstrates that the proposed single-objective PSA-based optimisation of longitudinal girders achieves weight reduction without degrading the strength of the transverse framing system; the transverse members across all deck levels retain adequate safety margins under the hogging design condition.

5.2. Full-ship response

As noted earlier, after completion of the optimisation, global finite element analyses were performed using the full-ship model with the optimised scantlings for the five loading conditions defined in Table 3, in order to compare and assess the structural responses before and after optimisation. Fig. 13 compares the von Mises stress distributions of the full-ship FE model between the original and optimised scantlings for (a) full-load still water, (b) vertical bending moment in sagging, (c) vertical bending moment in hogging, (d) transverse bending moment in sagging, (e) transverse bending moment in hogging.

Across all load cases, the optimised configuration exhibits stress patterns that are very similar to those of the original design, and in many regions the stress levels are slightly reduced or remain essentially unchanged:

In full load-still water condition, the overall hull girder stresses remain low in both designs. The optimised scantlings do not introduce any additional high-stress zones, indicating that the still-water strength is fully preserved.

For vertical bending, sagging (b) and hogging (c), the characteristic global bending stress distributions along the hull are maintained after optimisation. Peak von Mises stresses in the deck and bottom regions are comparable to, or marginally lower than, the original values and remain below the allowable limit. No new critical hot spots appear, confirming that the longitudinal strength under primary vertical bending is not compromised.

5.3. Ultimate strength

In this section, a one-slice hull girder model is employed to evaluate the change in ultimate strength before and after optimisation, and to assess its adequacy against the relevant classification society criteria.

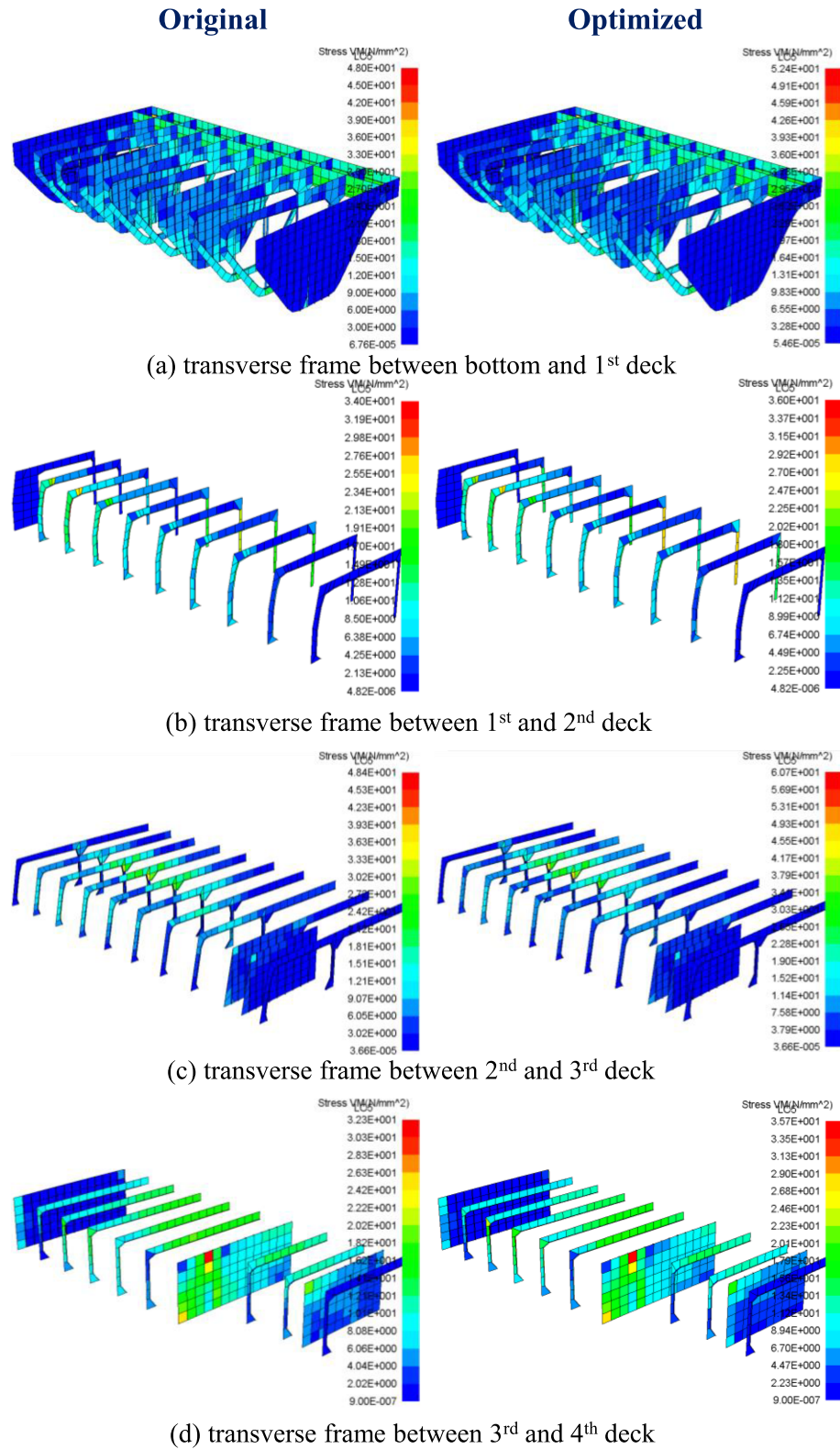


Fig. 12. Comparison of von Mises stress distribution for transverse frame in three-hold FE model under the rule-based hogging bending moment: (a) between bottom and 1st deck, (b) between 1st and 2nd, (c) between 2nd and 3rd, (d) between 3rd and 4th.

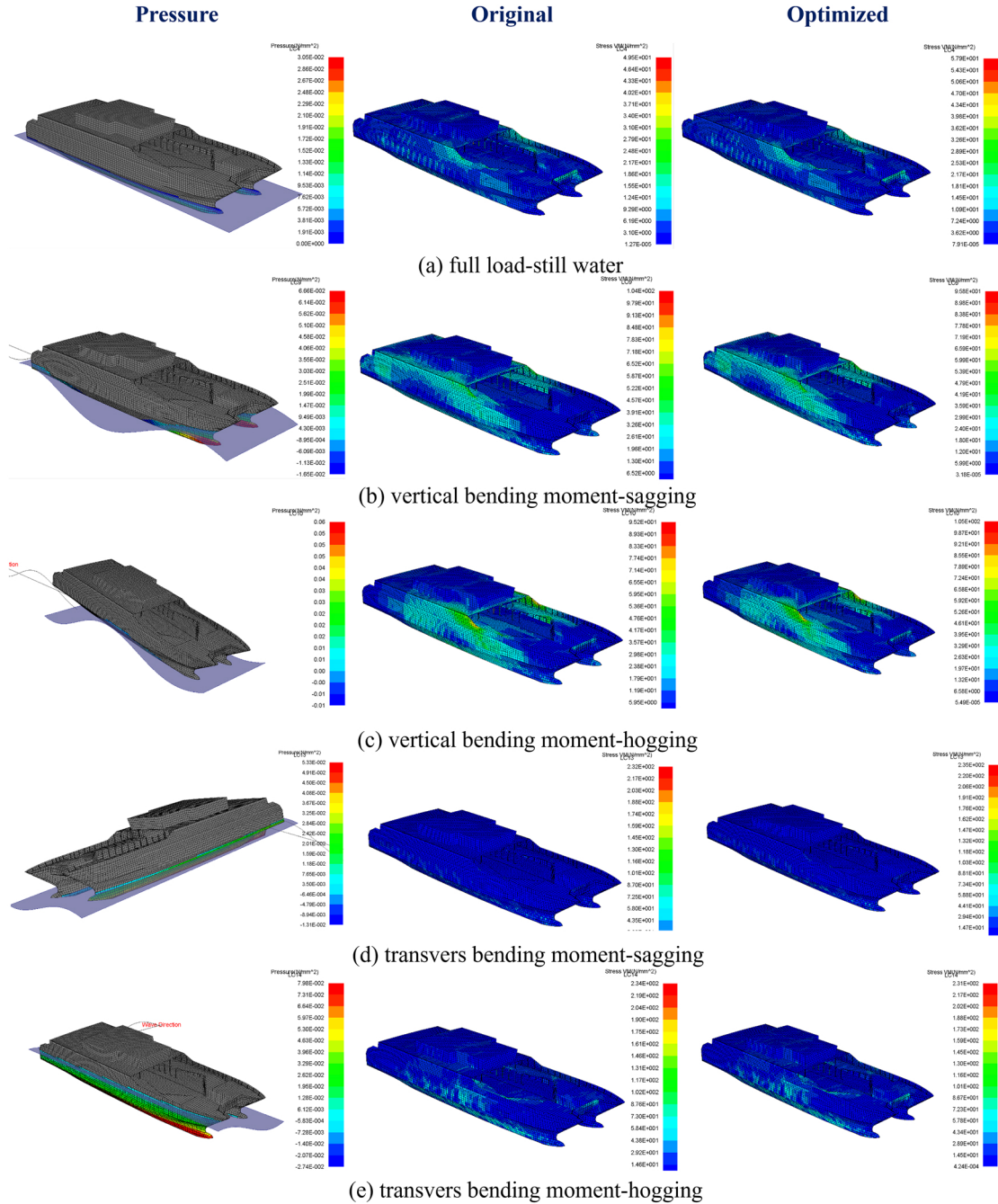


Fig. 13. Comparison of pressure and von Mises stress distribution for the full-ship FE model between the original and optimised scantlings for (a) full load–still water, (b) vertical bending moment in sagging, (c) vertical bending moment in hogging, (d) transverse bending moment in sagging, (e) transverse bending moment in hogging.

Fig. 14 presents the von Mises stress distributions obtained from the one-slice FE model for the sagging and hogging vertical bending moments, comparing the original and optimised scantlings. For both loading directions, the overall stress patterns of the optimised section closely follow those of the original design. The stress is smoothly distributed along the decks, side shell and inner structures, and the

local high-stress regions remain confined to the same limited connections as in the baseline case. No new hotspots appear and no significant increase in peak stress is observed after optimisation. This indicates that the longitudinal girder weight reduction does not adversely affect the stress state used as input for the ultimate strength assessment of the hull girder cross-section.

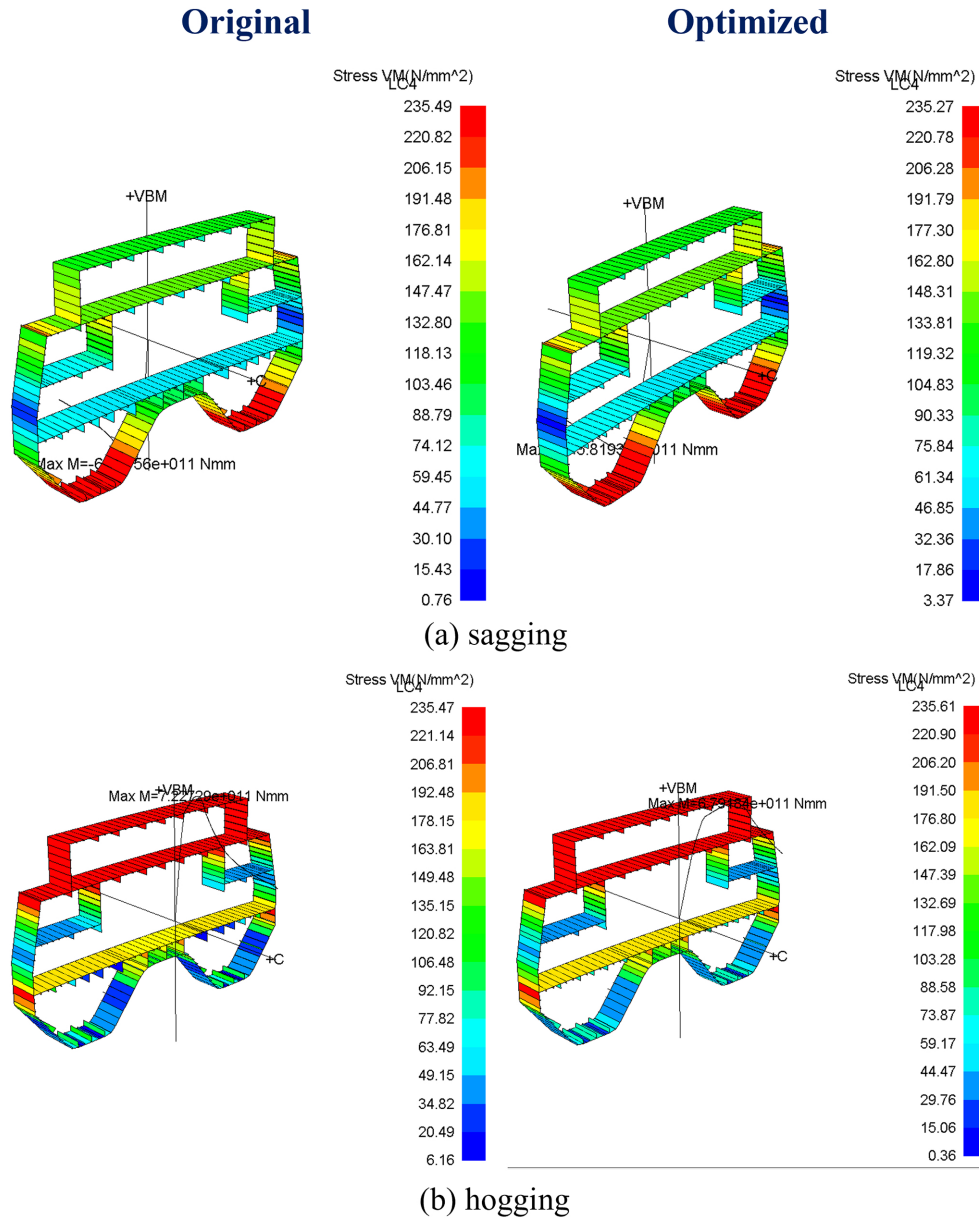


Fig. 14. Comparison of von Mises stress distribution for one-slice FE model: (a) sagging, (b) hogging.

Fig. 15 shows the vertical bending moment–curvature relationships and the corresponding ultimate hull girder strengths for the one-slice model, compared with the KR requirement (KR, 2024). One-slice hull girder ultimate strength assessment indicates that the optimisation leads to only a modest reduction in the hull girder capacity. In hogging, the ultimate bending moment decreases from 0.723 GNm to 0.679 GNm, corresponding to a 6.1% reduction, while in sagging it decreases from 0.614 GNm to 0.582 GNm, corresponding to a 5.2% reduction. Despite these reductions, the optimised scantlings still provide safety margins of approximately 10.9% in hogging and 13.5% in sagging relative to the KR

requirements, thereby confirming that the proposed optimisation maintains an adequate ultimate strength capacity of the hull girder.

The observed reductions in ultimate bending capacity after optimisation are primarily attributed to the reduction of sectional area and moment of inertia of the longitudinal girders near the design lower bounds, which leads to earlier onset of yielding and local buckling in critical deck and girder components. Nevertheless, the progressive collapse mechanism and overall load-carrying behaviour remain unchanged, and sufficient safety margins relative to the KR requirements are preserved.

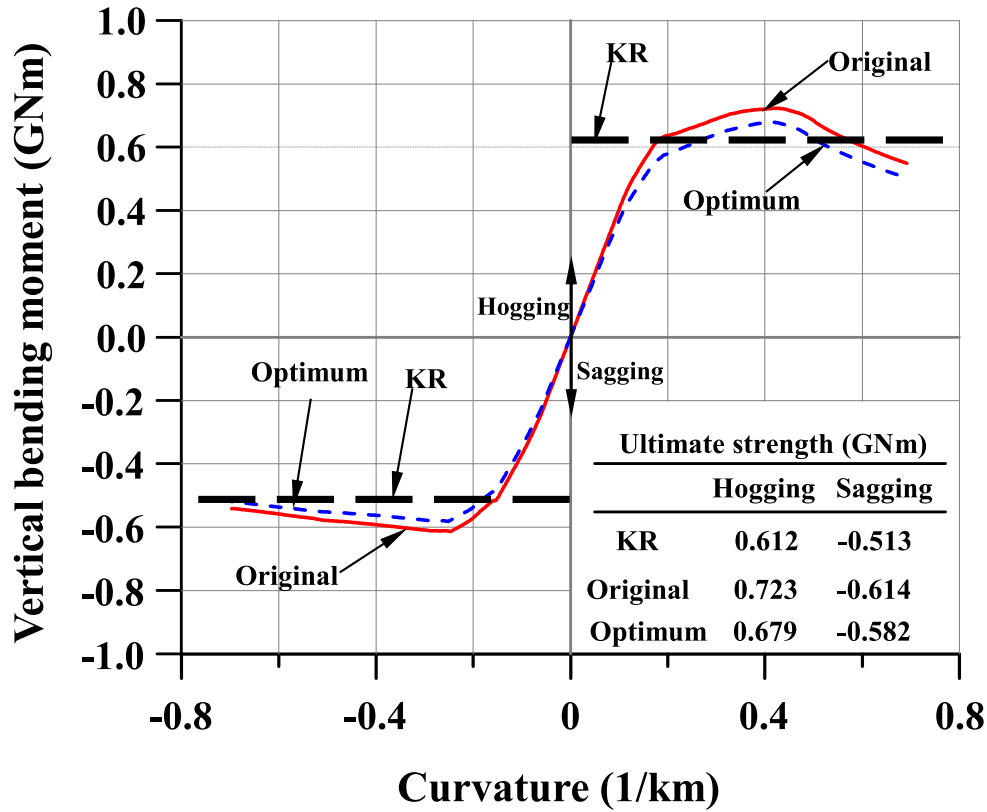


Fig. 15. Comparison of vertical bending moment–curvature relationships and ultimate hull girder strength for the one-slice model: KR requirement, original design, and optimised design (hogging and sagging).

5.4. Discussion

In the present study, the PSA scheme in MAESTRO is employed as a constrained single-objective search method. The scantling optimisation results in optimised longitudinal members that are concentrated near the lower bounds of the design domain, such as $300.0 \times 8.0 \times 100.0 \times 8.0$ mm. This tendency is not attributed to a deficiency of the optimisation algorithm, but is a direct consequence of the adopted problem formulation. The design variables, namely web height H_w , web thickness T_w , flange breadth B_f and flange thickness T_f are bounded within practically acceptable limits. The single-objective framework is constructed such that the primary objective is the reduction of structural weight, whereas strength and buckling are required to remain below the prescribed allowable limits and are thus treated effectively as constraints.

Under this configuration, the sectional properties increase monotonically with each design variable, so that any increase in H_w , T_w , B_f or T_f leads to a heavier structure without providing an explicit benefit in the objective space, as long as all candidate sections already satisfy the rule-based criteria. As a result, designs located away from the lower bounds are dom-

inated by lighter designs that still meet all constraints, and are therefore discarded by the PSA mechanism. The solution archive consequently collapses towards corner solutions at the minimum permissible scantlings, which explains the apparent clustering of the optimised sections at one boundary. This outcome indicates that, within the given bounds and constraint set, the initial scantlings were conservative and that the lower-bound configurations ensure sufficient safety. If additional performance measures such as deformation limits, local stiffness requirements, redundancy or fabrication preferences were to be included explicitly as separate objectives or tighter constraints, a more distributed set of non-dominated candidates and a wider variety of optimal scantling combinations would be expected.

The optimisation does not compromise structural safety: rule-based strength, buckling and serviceability checks remain satisfied; full-ship global responses under the governing vertical and transverse bending load cases are essentially unchanged compared with the baseline design; transverse hotspots occur at the same locations with similar or lower peak von Mises stresses, indicating that no new critical regions are introduced; and the one-slice ultimate strength assessment confirms that the optimised section still exceeds

the KR hull-girder requirements by approximately 10.9% in hogging and 13.5% in sagging. The PSA algorithm employed in this study follows the principles of stochastic global search, in which controlled random perturbations and probabilistic acceptance criteria enable the exploration of the discrete design space beyond local minima. When applied as a constrained single-objective scheme, the PSA mechanism effectively drives the solution towards the lightest feasible designs located near the admissible lower bounds while maintaining all structural constraints. Hence, the proposed optimisation-based framework reduces weight without degrading the ultimate or rule-based safety of the hull structure.

6. Conclusions

This study proposes a practical single-objective optimisation framework for the longitudinal girder scantlings of a 500-tonne steel catamaran, integrated with full-ship analysis and hull-girder ultimate strength verification. The framework supplements conventional rule-based and comparative baseline design by introducing an explicit optimisation stage based on nonlinear finite element analysis.

Three finite element models are used in a consistent framework: a full-ship model to define the global load environment and check overall responses, a three-hold model to optimise longitudinal girders under the governing KR-consistent bending moments, and a one-slice model to assess the ultimate strength of the critical transverse section. In the case study, optimisation of the longitudinal girders reduces the three-hold steel weight from 121.3 tonne to 115.8 tonne (4.53%) and the full-ship hull weight from 695.7 tonne to 669.2 tonne (3.81%), while preserving global load-carrying behaviour and avoiding new critical hotspots.

The one-slice ultimate strength assessment shows only modest reductions in hull-girder capacity—from 0.723 to 0.679 GNm (6.1%) in hogging and from 0.614 to 0.582 GNm (5.2%) in sagging—yet the optimised section still exceeds the KR requirements by about 10.9% and 13.5%, respectively. The clustering of optimal scantlings near the lower bounds of the admissible ranges indicates that the baseline design was conservative and that systematic optimisation can safely relax this conservatism without compromising rule-based or direct-strength criteria.

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Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this work.

Author contribution

Sang Eui Lee: Conceptualisation; methodology; finite element modelling; optimisation and formal analysis; investigation; validation; visualisation; writing original draft preparation; writing review and editing; project administration.

Data availability

The numerical model descriptions, loading conditions and optimisation settings used in this study are fully documented in the manuscript. The finite element input files and postprocessing scripts generated using the commercial MAESTRO solver are available from the corresponding author upon reasonable request, subject to software license conditions.

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