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A Review of Structural Optimization Design Schemes for Small and Medium-Sized Wooden Boats

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Abstract. As a significant milestone in the history of shipbuilding, wooden vessels—through their craftsmanship, structural design, and cultural connotations—continue to offer valuable insights for contemporary naval architecture. With the decline in practical functionality and research attention, structural optimization has become increasingly important—not only as a scientific validation of traditional craftsmanship, but also as a means of safeguarding and transmitting material culture. Drawing on case studies and comparative analysis, this paper reviews feasible approaches to structural optimization of small- and medium-sized wooden vessels from four perspectives: lightweight design, enhancement of crashworthiness, improvement of navigational stability, and material reinforcement, thereby providing a reference for the innovation and development of traditional craftsmanship.

Keywords: Traditional wooden ships; structural optimization; impact resistance; lightweight design.

1. Introduction

As one of the earliest forms of waterborne transportation, wooden vessels trace their history back to the Neolithic period [1]. As early as 8,000 years ago, ancient peoples were able to construct dugout canoes; by the Shang Dynasty, plank-built vessels had emerged, and by the Han Dynasty, multi-decked ships appeared—attesting to the evolution of shipbuilding technology and the advancement of ancient civilization. Wooden vessels played a significant role in both military and commercial activities, with the Jiangnan black-awning boat being particularly representative—combining practical utility with artistic value and embodying the rich regional culture and craftsmanship wisdom.

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At present, wooden vessels exhibit deficiencies in structural design, lightweighting, crashworthiness, and stability, which can pose safety risks and hinder the inheritance of traditional craftsmanship. This review synthesizes existing research and relevant case studies to summarize optimization experience, with the aim of providing a reference framework for subsequent scholars. It analyzes the structural optimization of traditional wooden vessels from four perspectives, explores key technical pathways and directions, and seeks to promote both the preservation and innovation of this cultural heritage.

2. Structural Optimization Design Methods for Small- and Medium-Sized Wooden Vessels

2.1. Achieving Lightweight Design

To achieve a lightweight hull design, this review adopts structural optimization methods for improvement. As shown in Fig. 1, the optimization types include size optimization, shape optimization, and topology optimization. Comparative analysis indicates that topology optimization, under predefined design spaces, loads, and boundary conditions, can automatically determine the optimal material distribution through algorithms, thereby offering a new pathway for ship lightweighting [5].

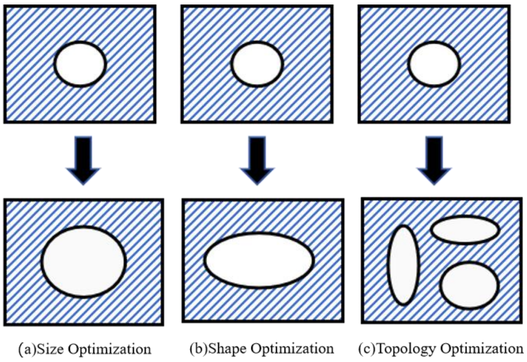

Figure 1. Three Levels of Structural Optimization

In the field of continuum structural topology optimization, the homogenization-based method [6] establishes a multiscale optimization model by periodically arranging microscopic unit-cell structures within the design domain. This method takes the key geometric parameters and spatial orientation of the unit cell as optimization variables, enabling systematic regulation of the mechanical properties of the macroscopic structure [7]. By dynamically adjusting the scale and morphology of the unit cell, this approach enables adaptive redistribution of materials within the design domain, enhancing configuration efficiency while meeting performance requirements. The homogenization method proposed by Bendsøe and Kikuchi [6] (as shown in Fig. 2) introduces the multiscale characteristics of composite materials into structural optimization, transforming shape optimization into the optimization of material property distribution, and, under multiphysics coupling conditions, balancing performance enhancement with lightweighting objectives.

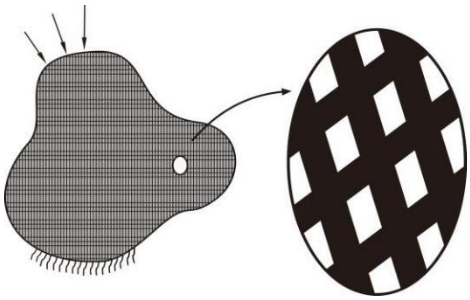

Figure 2. Schematic Diagram of Continuum Homogenization

The bidirectional evolutionary structural optimization (BESO) method proposed by Querin et al., along with its improved algorithms [8–11], can also be introduced. As shown in Fig. 3, the improved BESO further enhances convergence speed and optimization efficiency, providing a powerful numerical tool for the lightweight design of complex structures.Based on the element efficiency evaluation criterion, a material utilization assessment system is established to accurately identify and remove inefficient elements, while augmenting material in critical stress-path regions. This enables intelligent redistribution of structural materials and lays a theoretical foundation for hull opening optimization under multiple operating conditions. Using finite element stress analysis to identify low-stress regions and remove redundant material, and combining it with progressive iterative optimization, the hull framework evolves from a uniform grid to an efficient honeycomb topology. This approach holds significant value for reducing costs, improving resource utilization, and advancing the green and intelligent development of ships.

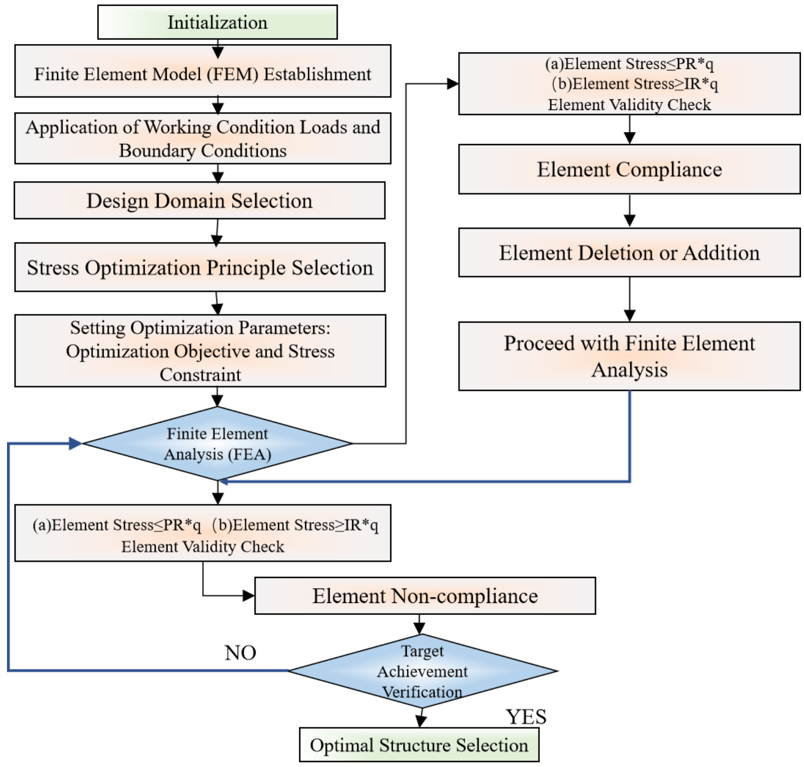

Figure 3. BESO Optimization Flowchart

2.2. Enhancing Crashworthiness

The energy-absorbing structure can adopt a single-hull sidewall with sandwich panels [12], in which an optimized combination of high-strength composite skins and lightweight core layers replaces the traditional outer plating. Under strict control of weight increments, this design leverages the multiscale effects and interfacial synergy of composite materials to significantly enhance dynamic impact energy absorption. Furthermore, the integrated sandwich structure replaces the conventional "outer plating + ribs" configuration, achieving coordinated optimization of load-bearing capacity, impact resistance, and lightweighting.

In his study, Wang et al. [13] combined the NOAHS II crashworthy structural concept with the dynamic progressive buckling characteristics of axially compressed thin-walled circular tubes, and proposed an improved double-hull structural design, termed CCT (Combined Crashworthy Topology). By optimizing the stiffness distribution and deformation patterns, this design not only improves overall rigidity but also effectively channels collision energy, enlarges the plastic deformation zone, and achieves dual performance enhancements.

A review of existing research indicates that, compared with the mature technologies in the field of automotive crash safety, studies on crashworthiness and collision protection structures in traditional wooden vessels remain insufficient. This paper introduces the design concept of automotive crashworthiness into the structural optimization of wooden vessels, establishing a cross-disciplinary comparative research framework to investigate the mechanism by which the geometric configuration of anti-collision main beams influences impact resistance. Inspired by typical bionic structures such as water droplets, eggshells, and turtle shells, three anti-collision main beam models were developed in LS-DYNA to simulate their dynamic responses under identical conditions, analyzing the patterns of loading, deformation, and energy dissipation [14] (as shown in Figure 4). The results indicate that the water drop–shaped main beam exhibits the best overall crashworthiness, providing both theoretical support and practical reference for the collision protection design of wooden vessels.

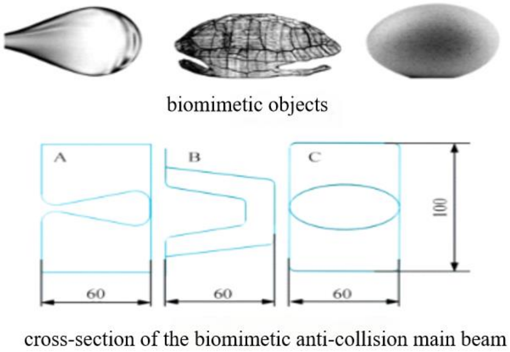

Figure 4. Bionic Anti-collision Main Beam[14]

As a core component of modern collision protection systems, the energy-absorbing box has been well validated in the safety design of automobiles and passenger vehicles. Liu Shi [15] systematically reviewed research on the structural optimization of energy-absorbing boxes and conducted coordinated optimization of collision beams and energy-absorbing boxes as an integrated system (as shown in Fig. 5). The study focused on analyzing the influence of parameters such as cross-sectional shape, cone angle design, and material properties on performance, and determined the optimal combination through multi-parameter coupling to achieve overall performance enhancement. This achievement offers a new perspective for the collision protection design of wooden vessels.

Figure 5. Automotive Anti-Crash Beam Structure[15]

2.3. Enhancing Navigational Stability

To address the common shortcomings of traditional small- and medium-sized vessels in maneuverability and speed within shallow waterways, the key design parameters of the hull form are systematically adjusted to achieve overall improvements in navigational performance.

An innovative design concept employing a large beam-to-draft ratio (B/T) is adopted, which significantly reduces draft depth while ensuring stability (as shown in Fig. 6). To overcome the limitation of single-propeller propulsion in balancing displacement and navigational performance, a multi-propeller coordinated propulsion system is introduced. Combined with hydrodynamic optimization of the hull lines and upgraded power configuration, this approach achieves breakthroughs in high-precision maneuvering and rapid response in shallow-water environments. The results show that, compared with conventional single-propeller designs, the new multi-propeller system significantly improves maneuverability and dynamic response characteristics while maintaining the same displacement. This design concept, which integrates hull form optimization with propulsion control, not only resolves the conflict between payload capacity and maneuverability in shallow-water vessels, but also provides a new technological pathway for enhancing the performance of inland and nearshore ships [16].

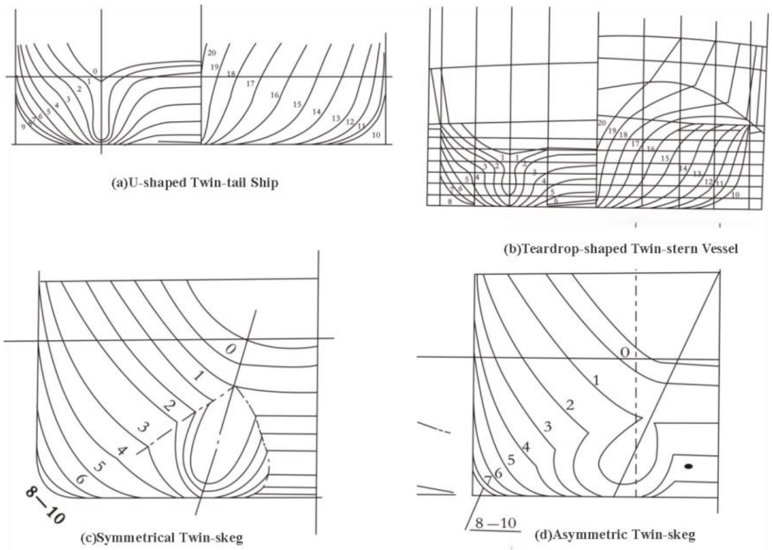

Figure 6. Twin-Stern Vessels with Varied Skeg Geometries

2.4. Material Renewal and Reinforcement

Numerous scholars in China have conducted systematic and in-depth studies on various types of composite materials, particularly the application of fiber-reinforced polymers (FRP) in the reinforcement of wooden beams [17, 18]. The research subjects include damaged wooden beams, intact wooden beams, and wooden beams formed by connected splicing. A review and comparative analysis of existing studies reveals that, regardless of whether FRP sheets or FRP plates are used for reinforcement, the load-bearing capacity and ductility indices of wooden beams in the aforementioned conditions show significant improvement [19]. Furthermore, combined results from bending tests and numerical analyses of wooden beams further confirm that increasing the FRP coverage ratio enables FRP sheet bonding to effectively enhance the ultimate load-bearing capacity of wooden beams [20], while also playing a positive role in delaying structural failure and improving failure modes.

However, existing literature still contains relatively limited research and experimental data on the direct application of FRP materials in the structural reinforcement of wooden vessels. Against this backdrop, drawing on the proven experience of FRP in reinforcing wooden beam structures, comparative analysis can offer a technological pathway and theoretical support for the application of FRP in wooden vessels. Compared with traditional wooden vessels, modern wooden ships can incorporate a variety of new materials into hull structural design to enhance overall performance, durability, and environmental friendliness. Among them, fiber-reinforced polymers (FRP), owing to their light weight, high strength, corrosion resistance, and excellent formability, offer significant advantages in the reinforcement and repair of wooden vessels. They not only enhance the structural strength and stiffness of the hull, but also extend service life, reduce maintenance costs, and show broad application prospects in the fields of green shipping and sustainable development.

3. Design Constraints and Challenges

(1) The optimization of wooden vessels must strike a balance between traditional craftsmanship and industrialized production, avoiding excessive reliance on CNC machining to ensure cultural heritage preservation.

(2) At the same time, in order to preserve traditional culture, it is essential to retain traditional construction techniques and forms as much as possible while applying modern technologies.

(3) The application of composite materials is still at a trial stage and remains costly, necessitating the development of cost-effective alternative materials and the assessment of their economic feasibility.

(4) At present, the optimization of wooden vessel structural design must strictly comply with existing regulations. However, due to the inherent rigidity and limitations of these provisions, they may, in certain cases, fail to fully meet the innovative design requirements of new wooden vessels.

4. Conclusion

China's shipbuilding industry is now among the largest in the world; however, in the context of complex water environments and intersecting rivers, the structural safety and stability of traditional wooden vessels remain in urgent need of improvement. This paper proposes structural optimization schemes for small- and medium-sized wooden vessels from four perspectives: lightweight design, crashworthiness enhancement, navigational stability improvement, and material renewal and reinforcement. By increasing structural strength and stiffness and optimizing hull configuration and layout, the crashworthiness can be improved and risks reduced; by enhancing stability, safety hazards such as capsizing can be mitigated; and through structural optimization, service life can be extended and maintenance costs reduced; broaden application fields to enhance suitability in industries such as tourism and sightseeing, as well as fishing, thereby expanding market potential. At present, research on the local details of traditional wooden vessels remains limited. Future work can proceed from specific optimization pathways, integrating finite element analysis and numerical simulation to carry out targeted studies.

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