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STUDY ON THE GEOMETRY OF COMPOSITE STRUCTURES USED IN NAVAL DESIGN, WITH EMPHASIS ON THE SHIP'S RUDDER

Abstract: *This paper examines the impact of composite structure geometry on naval design, with a particular emphasis on ship rudders. Key parameters such as shape, profile, thickness, fibre orientation, and angle of attack are analysed to determine their role in improving hydrodynamic efficiency, structural performance, and durability. The use of composite materials enables the development of lighter, stronger rudders with enhanced manoeuvrability and reduced hydrodynamic resistance. Optimized geometric configurations contribute to increased operational efficiency and extended service life. Further research is needed to refine design methodologies and explore new composite material applications to enhance the performance and reliability of ship rudders.*

Key words: *Composite materials, ship rudders, geometry, hydrodynamics, fiber orientation, naval design*

1. INTRODUCTION

The study of the geometry of composite structures in naval design focuses on how the shape and configuration of composite materials influence the performance and integrity of marine vessels. Composite materials, known for their high strength-to-weight ratios and corrosion resistance, are increasingly utilized in shipbuilding to enhance efficiency and durability [1].

Understanding the geometric aspects of these structures is crucial for optimizing their load-bearing capacities and hydrodynamic performance. For instance, research into composite marine T-joints has demonstrated that variations in geometry and the presence of disbonds can significantly affect structural behaviour under load [2].

Safe marine composite structures are created using design guides, emphasizing concepts and design equations pertinent to various geometries and load cases.

Advancements in computational techniques, including data-driven frameworks for parametric shape design and optimization, have furthered the ability to tailor composite structures to specific performance criteria. These approaches enable efficient exploration of design spaces, leading to innovative hull forms and structural configurations that meet stringent naval engineering requirements [3].

Overall, the geometry of composite structures plays a pivotal role in naval design, influencing factors ranging from structural integrity to hydrodynamic efficiency, thereby underscoring the importance of meticulous geometric analysis in the development of modern marine vessels.

2. COMPOSITES STRUCTURES IN NAVAL INDUSTRY

2.1 Applications of composite in naval structures

The integration of composite materials in naval engineering has expanded significantly, finding application in various structural components due to their superior strength-to-weight ratio, corrosion resistance, and adaptability. These materials have transformed ship design, offering enhanced performance, longevity, and efficiency across multiple aspects of naval architecture.

One key application of composite materials is in rudders, where they improve manoeuvrability and hydrodynamic efficiency while simultaneously reducing weight and maintenance costs. This advancement contributes to better fuel economy and overall vessel performance [4]. Similarly, composite hull structures provide increased impact resistance and a longer service life compared to traditional steel hulls, leading to reduced fuel consumption and operational costs [1].

In military and commercial vessels, composites are widely used in superstructures to decrease top-weight and enhance stability. Their lightweight properties make them particularly valuable for improving a ship's centre of gravity without compromising structural integrity [1].

Another crucial application is in propellers and shafts, where composite materials help reduce noise and vibration while increasing durability and resistance to harsh marine environments [4].

Deck structures and bulkheads also benefit from composites, as they are lighter and more corrosion-resistant than conventional materials, improving overall vessel performance and longevity [1]. Additionally, composite materials are used in masts and radar towers to minimize electromagnetic interference, thereby enhancing communication and sensor functionality [4].

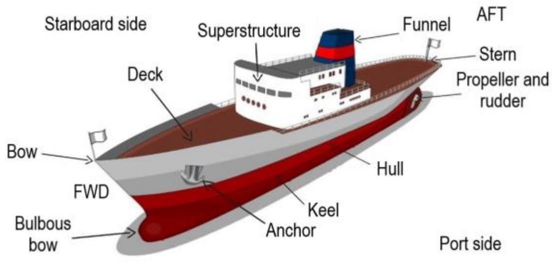

Figure 1 Main components of a ship [5]

The main components of a ship are included in the image above – Figure 1.

2.2 Composite material used in naval industry

The expansion of composite materials in naval industry has revolutionized modern shipbuilding by offering superior mechanical strength, corrosion resistance, and weight reduction compared to traditional materials like steel and aluminium. These advancements have led to increased fuel efficiency, enhanced durability, and improved hydrodynamic performance in maritime vessels. The most commonly used composite materials in the naval industry include Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), Aramid Fiber Composites, and Hybrid Composites (Figure 2). Their applications span across various structural and functional components of ships, contributing to lighter, stronger, and more efficient naval vessels [6].

Figure 2 Composites used in naval industry: a – GFRP [7], b – CFRP [8], c – Kevlar [9], d – Hybrid composites [10]

GFRP remains one of the most extensively used composite materials in shipbuilding due to its low cost, excellent corrosion resistance, and favourable strength-to-weight ratio. It is widely applied in the construction of hulls, decks, bulkheads, and superstructures, where both weight reduction and structural integrity are crucial. The non-corrosive nature of fiberglass composites significantly lowers maintenance costs compared to traditional metallic structures. Additionally, GFRP components are easily mouldable, allowing for intricate and hydrodynamically efficient designs that enhance vessel performance [11].

CFRP is recognized for its exceptional strength, stiffness, and lightweight characteristics, making it an ideal choice for high-speed naval vessels, military ships, and racing yachts. Unlike GFRP, which has moderate stiffness, CFRP offers a significantly higher elastic modulus and tensile strength, allowing for the construction of ultra-lightweight vessels with improved fuel efficiency and reduced hydrodynamic drag. However, the higher production costs of carbon fibre composites often limit their application to specialized, high-performance naval structures. Despite this, ongoing research into cost-efficient manufacturing processes is expected to expand the use of CFRP in mainstream naval architecture [12].

Aramid fibres, such as Kevlar, are primarily employed in naval engineering due to their high impact resistance, durability, and toughness. These composites are particularly beneficial for hull reinforcements, protective layers, and ballistic-resistant naval structures. Unlike GFRP and CFRP, aramid composites exhibit superior fracture toughness and energy absorption, making them highly effective in areas exposed to high-impact forces, extreme weather conditions, and ballistic threats. Additionally, their non-metallic nature enhances stealth capabilities by reducing electromagnetic reflectivity in military applications [6].

Hybrid composites are an innovative solution that combines multiple fibre types (e.g., glass-carbon, carbon-aramid) to optimize structural properties. These composites allow the customization of material performance by balancing strength, flexibility, and impact resistance. In naval applications, hybrid composites are increasingly used in superstructures, propellers, and masts, where a blend of lightweight properties and mechanical robustness is required. For instance, a carbon-aramid hybrid composite can provide the stiffness of CFRP while incorporating the impact resistance of Kevlar, making it an ideal choice for dynamic load-bearing components. As marine composite technology advances, hybrid materials are expected to dominate the future of naval engineering due to their versatility and enhanced performance [11].

The following table (Table 1) provides a comparative analysis of key mechanical and physical properties of composite materials used in shipbuilding:

Table 1

Mechanical and physical properties of composite materials used in shipbuilding [12]

Property	GFRP (Glass Fiber)	CFRP (Carbon Fiber)	Aramid Fiber (Kevlar)	Hybrid Composites
Density (g/cm^3)	1.5-2.0	1.6-1.8	1.4-1.5	Varies (1.4-1.8)
Tensile Strength (MPa)	600-1200	2500-6000	2500-3100	1200-4500
Elastic Modulus (GPa)	20-40	150-250	60-125	Varies (40-200)
Impact Resistance	Moderate	Low	High	Optimized Balance
Corrosion Resistance	High	High	High	High
Cost	Low	High	Moderate to High	Variable
Applications	Hulls, decks, bulkheads	High-speed vessels, superstructures	Hull reinforcement, armor protection	Propellers, masts, hybrid structural elements

The advancement of composite materials has significantly contributed to the efficiency, safety, and sustainability of modern vessels. GFRP remains the most widely used composite due to its affordability and versatility, whereas CFRP is preferred for high-performance applications requiring exceptional strength-to-weight ratios. Aramid composites provide superior impact resistance, making them ideal for protective and stealth applications in military vessels. Meanwhile, hybrid composites are paving the way for customizable naval solutions, offering a balance between multiple properties.

As marine composite technologies continue to evolve, the industry is shifting towards more efficient, lightweight, and durable materials, leading to reduced operational costs, improved vessel performance, and enhanced environmental sustainability. The future of naval architecture lies in innovative composite designs, ensuring safer, faster, and more fuel-efficient ships for both commercial and military applications [13].

3. GEOMETRY OF NAVAL COMPOSITE STRUCTURES

The geometry of naval composite structures is a key factor in optimizing the performance of maritime vessels. These materials have fundamentally changed the approach of the design of ships, allowing the creation of structures that are not only lightweight and durable but also highly efficient. The strategic application of composite materials enables the optimization of the geometry for various components, from hulls to rudders and propellers, ultimately improving vessel performance and longevity.

3.1 Hull geometry and optimization

One of the most crucial components in any naval vessel is the hull, which directly impacts the ship's performance in terms of strength, stability, and hydrodynamics. The geometry of the hull is critical because it influences the resistance the ship experiences as it moves through water, which affects fuel efficiency, speed, and manoeuvrability. Composite materials, due to their lighter weight compared to traditional materials like steel, have revolutionized hull design (Figure 3). The use of composites in hull construction helps reduce drag and enhance fuel efficiency, allowing ships to operate more economically. The design of composite hulls often incorporates complex geometries that include multi-layered structures with varying fibre orientations. These geometries are not only optimized for strength but also for hydrodynamic efficiency [14].

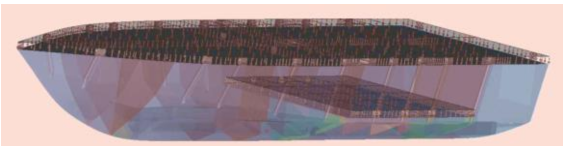

Figure 3 Composite hull design example [15]

Key considerations in hull geometry include layering and fibre orientation and thickness variation. The layers of composite material are oriented at specific angles (e.g., 0°, 45°, 90°) to provide strength in all necessary directions. This layered structure helps distribute the forces across the hull and enhances its overall mechanical properties. Technically, layering and fibre orientation in composites are tailored to provide maximum strength in all necessary directions, which is particularly important in areas of the hull subject to high stress [16].

Composite hulls may also feature varying thicknesses to accommodate different load-bearing requirements—thicker layers in high-stress areas such as the bow or stern, and thinner layers in less stressed regions [16].

Key to optimizing the hull's geometry is the ability to simulate and adjust the design using advanced computational tools. Finite Element Analysis (FEA) is commonly employed to assess the structural integrity of the hull under various conditions, helping in the process of refining the geometry to ensure it meets both strength and performance criteria.

3.2 Deck structures and bulkheads

Decks and bulkheads (Figure 4) are critical structural elements of a vessel that must balance strength with weight. One of the most effective ways to achieve this balance in composite materials is through the use of sandwich structures. A sandwich structure typically consists of a lightweight core—often made from materials such as foam or honeycomb—and outer composite skins. This configuration offers high strength while maintaining a low weight, which is crucial for improving the overall performance of the ship [17].

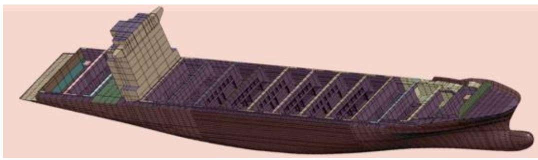

Figure 4 Composite bulkheads design example [15]

The geometry of composite decks and bulkheads is designed to distribute loads effectively across the structure, ensuring that weight is kept to a minimum without compromising the vessel's strength. For example, the hexagonal honeycomb core used in sandwich structures has a geometry that efficiently distributes stress, allowing the deck to resist bending and shear forces. Additionally, the outer skins of the composite are designed to handle compression and tension, ensuring that the deck remains strong under various load conditions [17].

Curved surfaces are often incorporated into the design of composite decks. These geometries enhance resistance to external loads, such as those from waves or cargo, and allow for better water flow across the deck, which is particularly important in dynamic marine environments. Composite materials provide the necessary flexibility to design decks and bulkheads with optimal geometries that enhance both performance and safety [17].

3.3 Rudders, propellers and performance

Rudders and propellers are two of the most important components of a ship when it comes to manoeuvrability and propulsion. The geometry of these parts has a significant impact on the vessel's hydrodynamic performance. In the design of composite rudders and propellers, the focus is on reducing drag and increasing thrust efficiency. Composites are particularly useful in these components because they offer lightweight properties combined with high strength and corrosion resistance [18].

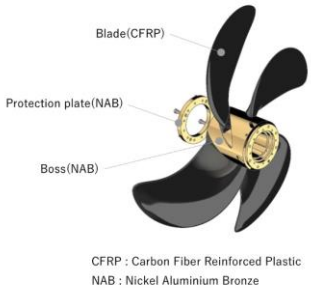

Figure 5 Composite propeller example [19]

Rudders and propellers made from composite materials are often designed with specialized geometries to maximize their performance. For example, the aerodynamic and hydrodynamic shapes of the blades are carefully designed to reduce drag and improve efficiency. The twist in propeller blades is one of the key geometric considerations that help optimize thrust (Figure 5). By varying the thickness of the blades along their length, with thicker sections near the base and thinner sections at the tips, designers can ensure that the propellers operate efficiently across different conditions, improving fuel efficiency and manoeuvrability [18].

Additionally, the reduction of cavitation is a critical design consideration. The geometry of the blades and their smooth, streamlined design helps reduce the formation of bubbles in the water, which can cause damage and reduce efficiency [18].

3.4 Masts, superstructures and stability

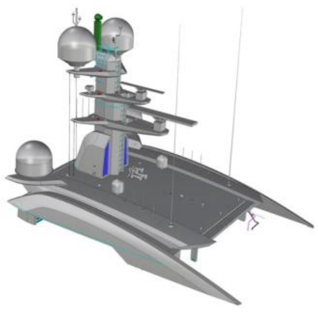

Figure 6 Composite radar masts [20]

Masts (Figure 6) and superstructures made from composite materials must be designed to withstand significant environmental loads, such as wind and waves, while keeping the weight of the upper structures low to ensure the vessel remains stable. The geometry of these structures is critical in maintaining the vessel's overall stability, as the weight distribution plays a key role in balancing the forces acting on the ship [21].

Composite materials provide flexibility in design, allowing for aerodynamic shapes that reduce wind resistance. The geometry of masts and superstructures is often optimized with streamlined, tapered shapes to minimize drag and improve the ship's overall stability in high winds. Additionally, the flexibility of composite materials enables these structures to endure dynamic forces without sacrificing strength or integrity [21].

The reduction of weight in these areas is essential for maintaining the vessel's balance, as excessive weight in the upper sections can raise the centre of gravity and affect stability. Composite materials, due to their high strength-to-weight ratios, enable the design of masts and superstructures that are both lightweight and capable of withstanding the environmental loads they will face at sea [21].

4. COMPOSITE RUDDERS

4.1 Naval rudders generalities

A rudder is a primary control surface used to steer ships, boats, submarines, and other watercraft (Figure 7). Typically mounted at the stern, the rudder operates by redirecting the flow of water, thereby inducing a turning motion in the vessel. Its fundamental design consists of a flat, smooth surface—often made of wood or metal—hinged along its forward edge to the sternpost. This configuration allows the rudder to pivot, creating unequal water pressures that facilitate directional changes [22].

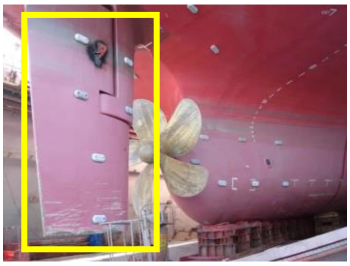

Figure 7 Ship rudder [23]

In contemporary maritime practice, various rudder designs are tailored to meet the specific requirements of different vessels (Figure 8). The balanced rudder features a portion of its surface positioned forward of the turning axis, which reduces the effort required to operate it, making it a popular choice for large ships. A variation of this design is the semi-balanced rudder, which integrates elements of both balanced and unbalanced rudders, striking a balance between manoeuvrability and structural simplicity. In contrast, the unbalanced rudder is entirely located aft of the turning axis, necessitating greater force to manoeuvre but offering a simpler construction [23].

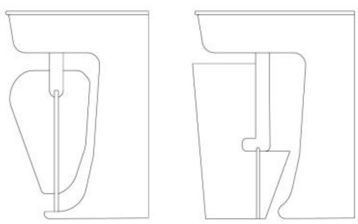

Figure 8 Balanced vs semi-balanced rudder

The placement of rudders is strategically considered in ship design. Positioning the rudder behind the propeller allows it to benefit from the increased velocity in the propeller's outflow, enhancing steering effectiveness. Conversely, a bow-mounted rudder is generally less effective due to hydrodynamic limitations, leading to larger turning radii and reduced manoeuvrability [24].

Understanding the mechanics of how a rudder facilitates turning is crucial. When the rudder is angled, it creates a pressure differential across its surfaces, generating a force that pivots the vessel about its centre of gravity. This action alters the ship's orientation and initiates a turn, with the effectiveness influenced by factors such as rudder angle, vessel speed, and hull design [25].

4.2 Optimization of composite rudders geometry

The use of composite materials in ship rudder design continues to evolve, offering new possibilities for enhancing vessel performance. By optimizing the rudder's shape, profile, thickness, fibre arrangement, and angle of attack, designers can achieve significant improvements in manoeuvrability, efficiency, and durability.

One of the most promising developments is the adoption of twisted rudder designs, where the angle of attack varies along the span of the rudder. Unlike conventional flat rudders, a twisted shape aligns more effectively with the water flow at different depths, reducing turbulence and cavitation. This not only enhances hydrodynamic efficiency but also extends the rudder's lifespan by minimizing structural stress. Composite materials allow for precise shaping of such complex geometries, which would be difficult or expensive to achieve with traditional metal construction.

The rudder profile is another crucial factor in optimizing performance. Traditional NACA airfoil profiles have been widely used, but modern computational fluid dynamics (CFD) simulations suggest that modified profiles, such as asymmetric hydrofoils, could provide higher lift with lower drag. The advantage of composites is that they can be moulded into these specialized profiles without adding excessive weight. Additionally, varying the thickness distribution along the rudder's span can further enhance performance by improving flow stability and reducing pressure fluctuations [26].

When it comes to rudder thickness, composite construction provides the flexibility to fine-tune structural characteristics. A strategically designed composite rudder can have a thinner leading edge to reduce resistance while maintaining sufficient thickness in critical load-bearing areas. By using variable thickness distributions, the rudder's first-order natural frequency can be optimized, reducing vibrations and enhancing stability.

The arrangement and orientation of composite fibres also play a fundamental role in structural strength and flexibility. Unlike metals, which have isotropic properties, composites allow designers to tailor mechanical properties by adjusting fibre orientation. For instance, carbon fibre layers aligned with the expected stress directions can maximize strength while reducing unnecessary weight. By carefully layering high-strength fibres at precise angles, rudders can be made both more durable and more responsive to hydrodynamic forces [27].

Finally, the angle of attack can be optimized to enhance manoeuvrability and propulsion efficiency. Unlike traditional fixed-angle rudders, composite rudders could incorporate slight variations in attack angles along their height, optimizing the flow at different depths. This could be particularly useful in minimizing energy losses caused by turbulent water flow near the propeller [28].

5. CONCLUSIONS

This study investigated how the geometry of composite structures—specifically in ship rudders—affects naval design. It shows that geometric configuration plays a crucial role in improving hydrodynamic performance, structural resilience, and overall vessel efficiency.

By analysing key parameters such as shape, profile, thickness, fibre orientation, and angle of attack, it was demonstrated their combined influence on reducing drag, enhancing lift, and optimizing strength-to-weight ratios. For example, proper fibre orientation and thickness distribution improve structural integrity without adding mass, while the rudder's shape and angle of attack directly affect manoeuvrability and hydrodynamic efficiency.

Thus, the impact of composite geometry lies in its ability to enable more agile, fuel-efficient, and durable ship designs—benefits that are further enhanced by using advanced materials and simulation tools like CFD and FEA.

Future work should expand on these findings by testing new geometric layouts and composite formulations, ensuring that naval components such as rudders can fully leverage these design advantages under real-world operating conditions.

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