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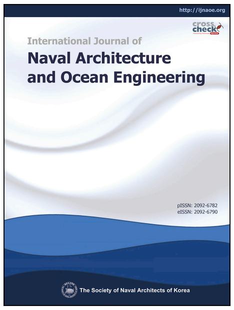

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Review Article

Comparison of Structural Design and Future Trends in Composite Hulls: a Regulatory Review

Zhiqiang Han[a], Jaewon Jang[b], Jean-Baptiste R. G. Souppez[c], Hyoung-Seock Seo[d,*], Daekyun Oh[e,*]

[a] School of Naval Architecture and Maritime, Zhejiang Ocean University, Zhoushan, China; hzq910413@zjou.edu.cn
[b] Department of Ocean System Engineering, Graduate School, Mokpo National Maritime University, South Korea; wodnjs1910@gmail.com
[c] Department of Mechanical, Biomedical and Design Engineering, School of Engineering and Technology, College of Engineering and Physical Sciences, Aston University, UK; j.souppez@aston.ac.uk
[d] School of Naval Architecture and Ocean Engineering, University of Ulsan, South Korea; seohs@ulsan.ac.kr
[e] Department of Naval Architecture and Ocean Engineering, Mokpo National Maritime University, South Korea; dkoh@mmu.ac.kr
* Correspondence: seohs@ulsan.ac.kr (H.-S. Seo), dkoh@mmu.ac.kr (D. Oh); Tel.: +82-61-240-7318

Abstract: Recently, the International Organization for Standardization (ISO) standards associated with composite hull-structure design, including the method for estimating the mechanical properties of laminates necessary for design, have been revised. This study reviews the revisions concerning materials and analyzes the design trend of composite hull structures by comparing eight related rules, including classification society and domestic rules. The results reveal that the current design trend of hull laminates is to thoroughly consider the impact of several variables, including the weight fraction of reinforcement (glass content; Gc), fabric combination, and fabrication method, on the laminate properties. For illustration, these effects were verified with a typical glass-fiber-reinforced plastic vessel based on a case study, the experimental results of extant studies, and current standards. The industry design conditions, normal Gc (0.367) and high Gc (0.600), were selected and applied to two fabric combinations: chopped strand mat and chopped strand–woven roving. The hull laminate design results based on the revised ISO standards (ISO 12215) satisfied the safety and weight requirements for normal Gc in both cases. This may be attributed to the high mechanical properties suggested in the current standards regardless of how they reflect the effects of changes in fabric type, combination, and method on the mechanical properties of the laminates. For high Gc, the combination material case satisfied the safety requirements to a greater extent. and this can also be made lightweight. In contrast, the single material case based on the revised ISO standard may result in safety issues, mainly because the revised ISO standard reflects the adverse effects of design variables such as Gc and fabric blends on the laminate fabrication quality. Further, non-ISO rules should be revised in the future to reflect the effects of each variable in the material design according to the research trends of composite materials.

Keywords: composite hull material, fiber reinforced plastic, ISO 12215, FRP ship, ship design

1. Introduction

Composite materials are widely used in various industrial sectors due to their long lifespans and excellent operational characteristics, among other attributes. However, materials such as glass fiber-reinforced plastics (GFRP) or carbon fiber-reinforced plastics (CFRP) possess intrinsic defects such as voids, pores, impurities, and resin-rich regions, owing to environmental factors such as temperature and humidity, as well as the operator's skill level and the fabrication technique employed (Cho and Lee, 2021; Han et al, 2020a, 2021a, 2021b; Kim et al, 2014, 2022; Mouritz, 2000).

Because defects have a considerable impact on the mechanical properties of composites, they have been extensively studied, with the primary focus being their characteristics and mechanical effects (Bhat et al., 2019; Chandel et al., 2021; Heckadka et al., 2015; Lee and Soutis, 2005; Mariatti and Chum, 2005; Rashid et al., 2019; Srivastava and Singh, 2007; Ujianto et al., 2020). Studies indicate that a higher laminate thickness induces manufacturing defects such as voids (Bhat et al., 2019; Han et al., 2021a, 2021b; Lee and Soutis, 2005). Furthermore, the fabric orientation and laminate stacking schedules vary significantly, which impacts the mechanical properties of the laminate structure and fabrication quality (Chandel et al., 2021; Heckadka et al., 2015; Kulhan et al., 2022; Luan et al., 2019; Mariatti and Chum, 2005; Rashid et al., 2019; Srivastava and Singh, 2007; Ujianto et al., 2020). For example, Rashid et al. (2019) comparatively analyzed the laminate tensile strength test results for three combinations ([CSM]n, [WR]n, and [CSM/WR]n; n is the ply number) of two types of fabric: E-glass fiber chopped strand mat (CSM) and woven roving (WR). The tensile strength of the composite [CSM/WR]n was higher than that of the single materials ([CSM]n, [WR]n). The combination of WR and CSM helped improve both the directional strength characteristics and interlaminar bonding strength, and further reduced the content of inner defects such as voids.

The increasing adoption of composite materials, particularly in the maritime industry, may be attributed to their exceptional characteristics that enable flexible applications. Because of their excellent performance and cost-effectiveness, GFRP composites are the most common materials for manufacturing maritime structures. The design and manufacturing of composite ships is complex. The displacement of ship, speed, division, and other factors related to the principal particulars of a ship, including stiffener spacing and design pressure, must be considered, along with the mechanical properties of composite laminates (Oh et al, 2014; Song and Oh, 2016). The mechanical properties of the laminate are affected by fabric type, combination, and fiber orientation; they are expressed in terms of weight (glass content, Gc) or volume fractions of the fiber and resin constituting the laminates. The correlation between mechanical properties and various composite design conditions (Gc, fabric combination, and stacking schedules) must be carefully examined to realize safe and rational structural design under the required conditions, such as the principal particulars. The products must be fabricated according to the design conditions, because the fabrication quality is related to the structural stability and has a significant impact on the mechanical properties of the laminate (Bhat et al., 2019; Chandel et al., 2021; Cho and Lee, 2012; Han et al., 2020a, 2021a, 2021b; Heckadka et al., 2015; Kim et al., 2014, 2022; Kulhan et al., 2022; Lee and Soutis, 2005; Luan et al., 2019; Mariatti and Chum, 2005; Mouritz, 2000; Rashid et al., 2019; Srivastava and Singh, 2007; Ujianto et al., 2020). A low fabrication quality will result in a decrease in the laminate strength, which will warrant a thicker plate. Consequently, a high number of raw materials is required to satisfy the safety requirements of hull structures.

The literature contains significant research on the reduction of the weight of composite structures in the shipbuilding industry. A structure with low weight has a reduced fuel consumption and operational cost and an increased speed. This also results in an increase in energy efficiency. Low structural weight yields environmental benefits, such as decreased material requirements and wake wash (Barsotti et al., 2020; Greer et al., 2019; Han et al., 2020b, 2020c, 2021c; Jang et al., 2019; Jeong et al., 2020; Kim and Kim, 2008; Oh et al., 2014, 2018, 2019, 2020; Satheesh et al., 2010; Song and Oh, 2016; Stenius et al., 2011; Tawfik et al., 2017; Tuswan et al., 2019; Yum and Yoo, 2016). Several studies have attempted to reduce the structural weight by fabricating the chassis from CFRP, which has high strength and extremely low weight (Barsotti et al., 2020; Han et al., 2020b; Oh et al., 2014, 2018; Stenius et al., 2020). Most composite vessels are made of GFRP (Greer et al., 2019; Jeong et al., 2020). Hence, research on GFRP vessels in terms of composite optimization is being actively conducted based on genetic algorithms (Kim and Kim, 2008; Lorimer and Allen, 2022; Satheesh et al., 2010), the finite element method (FEM; Tuswan et al., 2019; Yum and Yoo, 2016), and the division and stiffener arrangement optimal design algorithm (Stenius et al., 2011). Unlike previous studies, this review includes a composite material lightweight design algorithm, which is based on the analysis of the relationship between design condition (Gc, fabric combination), mechanical properties, and required thickness according to the specified rule (Han et al., 2020c, 2021c; Jang et al., 2019; Oh et al., 2020). The ship to which this algorithm is applied has approximately 10 % less hull weight than vessels in similar tonnage classes. It also has a positive environmental impact with improved operational efficiency and reduction in raw materials (Han et al., 2020c; Jeong et al., 2020; Oh et al., 2019).

The design and construction of GFRP small vessels, such as fishing boats, pleasure boats, and yachts, comply with the International Organization for Standardization (ISO) 12215 (2008) and relevant classification society rules. Recently, the ISO 12215-5 (2019) standard was amended to consider various design elements during the design process of composite hull structures.

This study aims to analyze the changes in the design trends of composite hull structures by focusing on the revisions to the standards concerning the composite hull design, including those made in ISO 12215 (2019). Several classification society rules need to be followed to determine the dimensions of a ship, such as composite hull structure design rules of British Lloyd's Register (LR; 2021), Italian Registro Italiano Navale (RINA; 2022), Korean Register (KR; 2018), and China Classification Society (CCS; 2019), and domestic organizations such as Korea Maritime Transportation Safety Authority (KOMSA; 2021) and China Maritime Safety Administration (MSA; 2019).

2. The Effect of Changes in Composite Design Conditions on Laminate Structure

The thickness of composite hull plates significantly varies with the size of the structure and the application. A typical laminate thickness for an aircraft is 2–3 mm, while GFRP ships possess a hull-plate thickness of 10 mm or higher (Mouritz, 2020). In the case of naval and coast guard ships, the thickness may be in the order of a few tens of millimeters (Mouritz, 2020). High-quality fabrication according to the specified design thickness is prerequisite to ensuring the safety of the composite hull structure. However, the laminate is fabricated from two raw materials—fibers and resins—making it difficult to machine the composite hull plate to the required thickness. This is particularly relevant when fabricating thick composite hull plates.

Fishing boats and yachts, which constitute a large portion of composite vessels, are frequently designed based on experiences and traditions, and the majority are mostly constructed at small yards. Thus, the hand lay-up method is adopted instead of automated methods such as vacuum infusion (Han et al., 2020a, 2021a, 2021b). The design and drying environments are the main reasons resins are more frequently used than fibers, which further reduces the structural performance of the GFRP structure (Han et al., 2020c; Jang et al., 2019). The fiber weight fraction is significant in determining the thickness of the laminate in composite structures and may help determine the fabrication quality. The proper adjustment of this weight fraction is strongly correlated with both strength and weight of laminate structures, as well as the fabrication quality (Han et al., 2021c; Oh et al., 2019, 2020, 2022).

The E-glass CSM and WR fabrics are widely adopted composite fabrics for manufacturing GFRP small vessel structures. The combination of CSM and WR yields a higher weight per unit area, which helps achieve directional strength characteristics and enhances the resistance to impact on the hull plate (Scott, 1996). However, the enhanced strength of CSM and WR laminates can only be achieved through a suitable combination; otherwise, the combination itself may result in an increased number of voids and degradation of fabrication quality (Abdurohman et al., 2018; Lee et al., 2021; Oh et al., 2022).

Factors such as composite design conditions (Gc and fabric combination) and uncertainty in the fabrication quality significantly influence the mechanical properties of laminates. ISO 12215 (2008) considers the types of E-glass fiber and resin matrix, fabric type, and impact of Gc. However, the effects of fabric type (CSM and WR) and combination according to the design conditions of GFRP small vessels are not employed in the formula for estimating the mechanical properties of composite laminates. Moreover, changes in the fabrication quality with the composite design conditions are also not reflected in the estimation. The formula for estimating the mechanical properties according to the composite design condition, which are frequently considered in ISO 12215 (2019) for the design of a composite hull structure, has been revised to consider the Gc, fabric type of glass fiber, and changes in fabrication quality.

3. Composite Design Conditions in ISO Standards and Classification Society Rules

In this section, ISO 12215 (2008) is compared with the classification society rules of composite vessels. The design formula for the single-skin-type external plate, which accounts for the largest portion of the hull and receives the heaviest load, was compared. Table 1 summarizes the comparison of the proposed formulas according to each design rule. Figure 1 illustrates the flowchart of the similarities and differences between the design rules.

Table 1. Determination of thickness for composite hull laminate according to different design rules

Design Rule	Required Thickness (T) Estimation

ISO 12215 (2008)	T = [Stiffener spacing] × [Design pressure] / [Mechanical properties] × [Coefficient of hull shape]
RINA (2022)	T = [Stiffener spacing] × [Design pressure] / [Mechanical properties] × [Coefficient of hull shape]
LR (2021)	T = [Stiffener spacing] × [Design pressure & Coefficient of hull shape] / [Mechanical properties]
KR (2018)	T = [Stiffener spacing] × [Design pressure] / [Mechanical properties] × [Coefficient of hull shape]
CCS (2021)	T = [Stiffener spacing] × [Design pressure] / [Mechanical properties] × [Coefficient of hull shape]
KOMSA (2021)	T = [Ordinary stiffener spacing] × [Hull length + Draft]$^{0.5}$
China MSA (2019)	T = [Ordinary stiffener spacing] × [Hull length + Draft]$^{0.5}$

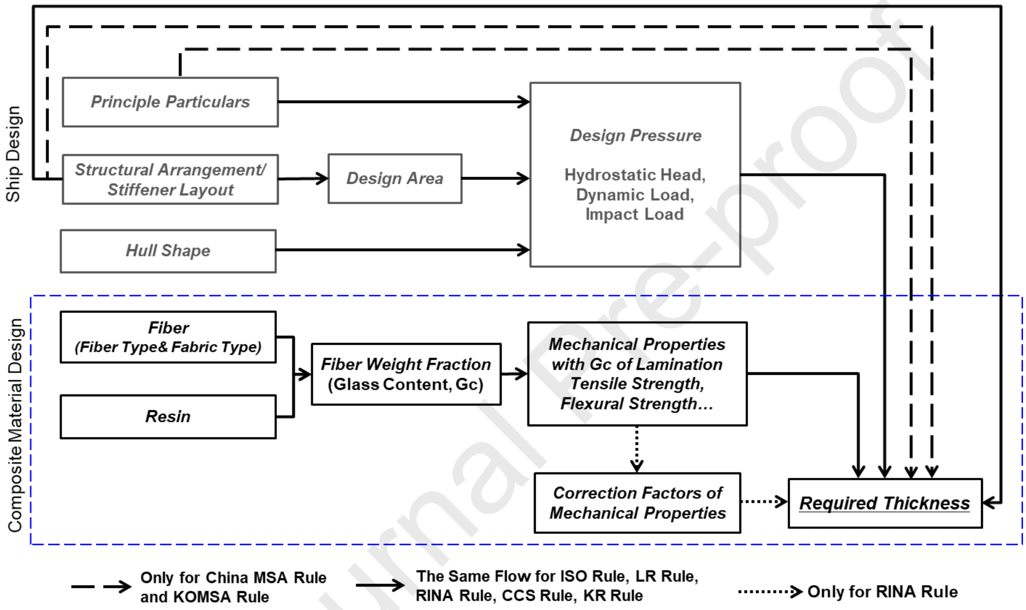
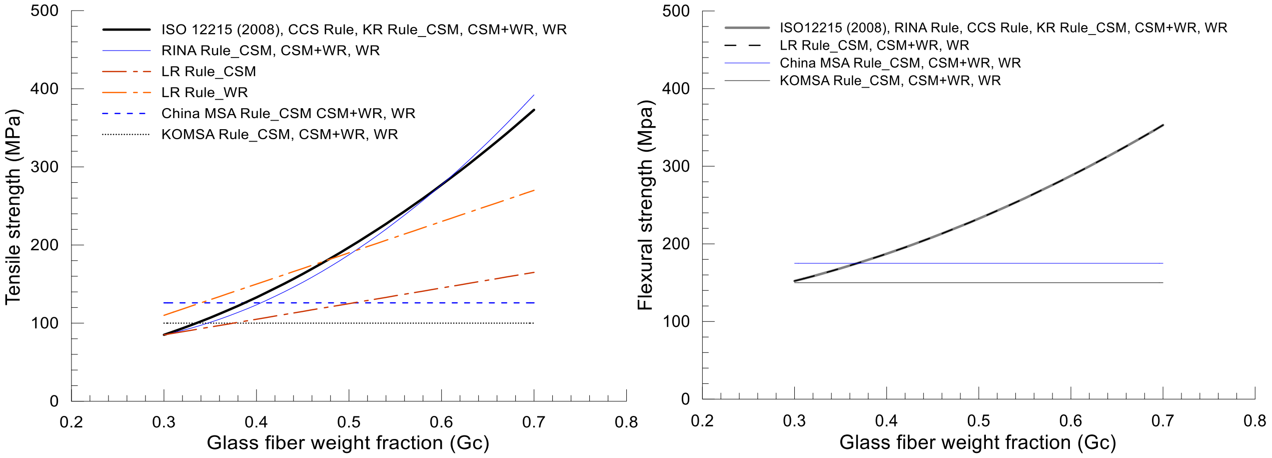


Figure 1. Fiber-reinforced plastic (FRP) hull structure scantling process mentioned in ISO standard (2008) and classifications (Han et al., 2020c; Jang et al., 2019; Oh et al., 2020).

As indicated in Figure 1 and Table 1, the composite hull design process based on each design rule can be approximately categorized into two groups. First, ISO standards and the classification society rules, such as the RINA, LR, KR, and CCS, all consider the principal particulars of a ship, subdivision, and stiffener layout, and other ship design variables such as pressure (hydrostatic head, wave, and impact pressures) acting on the hull in the composite hull structure design process. They also consider factors such as fiber type, fabric type, Gc, and mechanical properties according to the Gc. In contrast, rules specific to small coastal vessels, such as KOMSA and China MSA, consider the principal particulars and stiffener spacing as the primary factors affecting the required thickness; they do not consider fiber type, fabric type, and Gc. We presumed that these rules considered the margin for thickness despite being simpler than other classification rules. Figure 2 displays the trends of tensile strength and flexural strength with a variation in the Gc for the theoretical formulae proposed according to each rule.



(a) (b)

Figure 2. Comparison of mechanical property estimations with each design rule: (a) tensile strength (CSM, WR, CSM + WR); (b) flexural strength (CSM, WR, CSM + WR).

Typically, the strength increases with the Gc. The KOMSA and China MSA rules, which do not consider Gc, suggest the minimum requirements. In general, E-glass fiber is most commonly used, laminates are rarely fabricated as CSM and more frequently as a combination of CSM and WR. Figure 2 illustrates the plots of CSM alone and CSM + WR composite for each rule considering the aforementioned factors. The results show that, except for the LR rule, the classification rules do not consider the combination of fabric type.

Fiber combination is an important variable for determining the mechanical properties of laminates. Notably, laminate structures of GFRP small vessels are frequently fabricated from a combination of CSM and WR, mainly because it has a positive impact on their strength with the increase in Gc. However, this is not applicable to all cases (Han et al., 2021c; Oh et al., 2020, 2022). Further, composite fabrics are known to improve mechanical properties and interlaminar bonding, and consequently reduce intrinsic defects such as voids, thus enhancing the fabrication quality (Oh et al., 2022; Rashid et al., 2019; Scott, 1996).

4. Changes in Composite Hull Structure Design Rules

The most noticeable change in the design of composite hull structures according to ISO 12215 (2019), is the improvement in the mechanical properties of laminates. In addition to the combination of fabrics, which is frequently used in laminate production, the quality factor according to the difference between fabrication methods was also considered. Figure 3 displays the flowchart of the scantling process of a composite hull structure, as specified in ISO 12215 (2019).

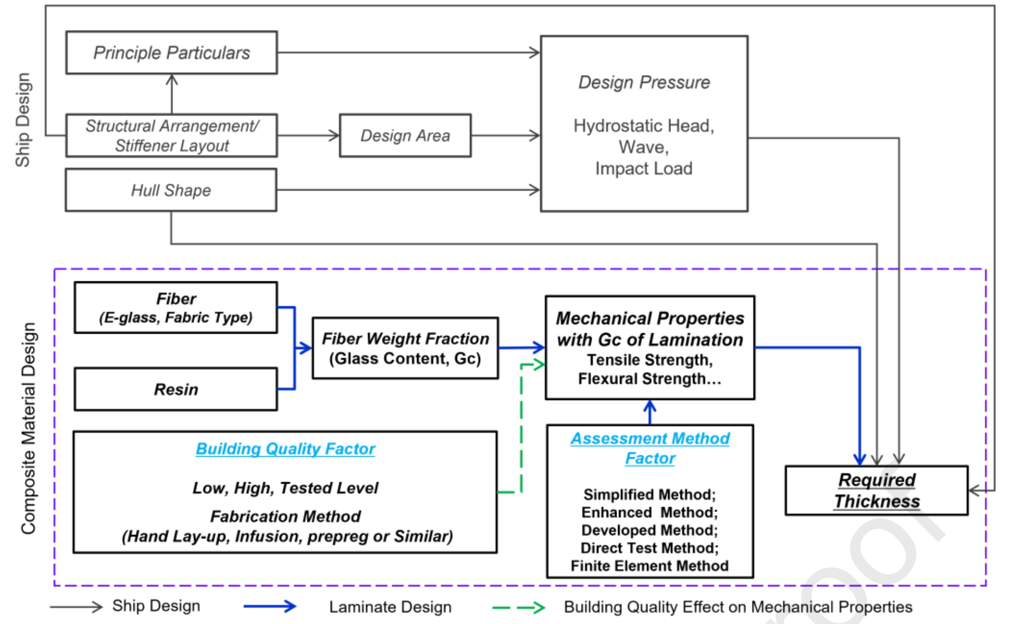


Figure 3. Fiber-reinforced plastic hull laminate scantling flowchart from ISO 12215 (2019).

ISO 12215 (2008) suggested a formula for estimating the mechanical properties regardless of fabric type and combination. Consequently, the fiber orientation did not reflect the impact of the mechanical properties of the laminate. However, ISO 12215 (2019) reflects this effect and suggests suitable estimation theoretical formulae. Graphs of the tensile and flexural strength suggested in ISO 12215 (2008, 2019) are depicted in Figure 4.

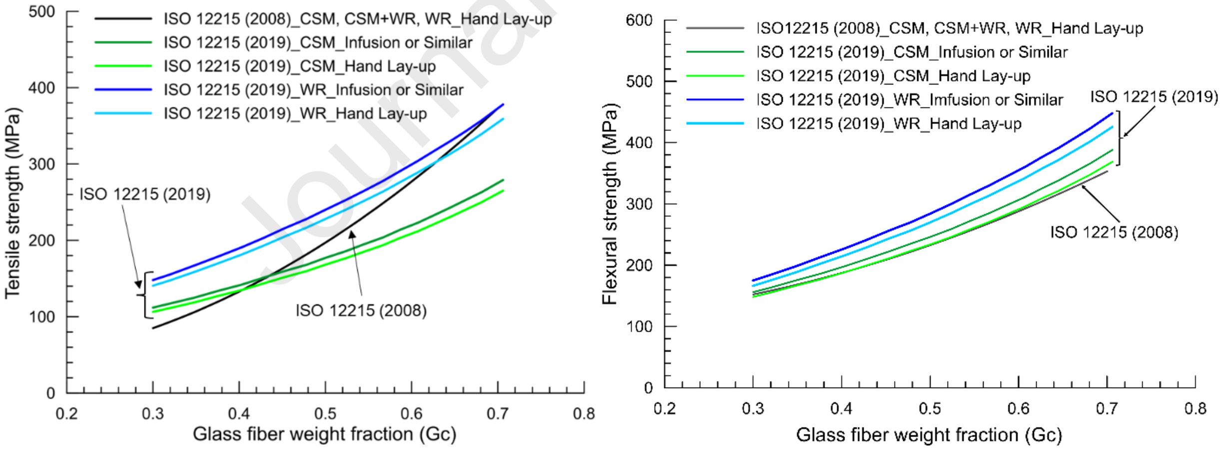


Figure 4. Comparison of composite mechanical properties suggested in ISO 12215 (2008, 2019).

As observed in Figure 4, the estimation results of the WR fabric's mechanical properties (flexural and tensile strength) according to the Gc in ISO 12215 (2019) are better than those in ISO 12215 (2008), for almost all Gc sections. The tensile strength of the CSM fabric is higher until the Gc is 0.43, and subsequently reduces to below that specified in ISO 12215 (2008). The flexural strength of the CSM + WR fabric according to the Gc in ISO 12215 (2019) is higher than that in ISO 12215 (2008), for all Gc values. The infusion method yielded a higher tensile (by approximately 5 %) and flexural strength than the hand lay-up method. In ISO 12215 (2019), the effects of the composite laminate's manufacturing quality according to the fabrication method and other variables are reflected in the estimation of the mechanical properties of the laminate (Souppez and Laci, 2022).

ISO 12215 (2008) suggested the nominal Gc for a simple surface (external plate or deck) and complex surface (top hat stiffener) and a fabrication method as a guideline. While resin impregnation and wetting-out are easy to perform on a simple surface, they are not suitable for a complex surface (ISO, 2008, 2019). Accordingly, the nominal Gc guideline for laminate fabrication can be viewed as an attempt to secure the manufacturing quality of the hull structure. However, this is not reflected in the estimation of mechanical properties of the laminate according to the Gc, which is required for composite hull design. In contrast, ISO 12215 (2019) additionally recommends the composite laminate's manufacturing-quality factors, which are also used when estimating the mechanical properties of the laminate according to the Gc (Figures 3 and 4). This factor is summarized in Table 2; the real Gc of a laminate obtained from a burn-off test or theoretical calculation is defined as the evaluation metric, in which the definition of the factor may vary with the fabrication method.

Table 2. Boat manufacturing-quality factors presented in ISO 12215 (2019).

Quality	Builder characteristics	Value	
		Hand lay-up	Infusion or similar
Tested	Mechanical properties of laminates are produced, as constructed, according to a mechanical characteristics test (modulus, breaking strains, etc.).	1	1
High	Fiber mass content monitoring obtained either from sample thickness with theoretical approach or burning process; for range of representative lay-ups.	0.95	1
Low	No measurements or checking on fiber mass content. Volume content is taken from ISO, according to relevant building process (minimum value where there is a range).	0.75	0.80

Table 3. Assessment method factor suggested by ISO 12215 (2019).

Assessment method	Characteristics	Value
Simplified	The simplified method provides a basic equation for the strength-driven plate thickness, assuming an embedded stiffener spacing beam, under a uniformly distributed load. This method is only valid for isotropic laminates made from the fiberglass plies	0.90
Enhanced	The enhanced method with a ply-by-ply analysis is applicable to laminates made of the same materials as in the simplified method, in addition to general orthotropic materials, considering the shear force and bending moment in both directions of the plates and double curvature.	0.95
Developed	The developed method is valid for all types of laminate, including the non-balanced ones. Inputs are the same as that for the enhanced method. It uses the classic laminate theory wherein the laminates are analyzed ply-by-ply, but generally the strain or stresses are verified in the two directions of a laminate panel.	1
Direct Test	Mechanical testing can be conducted rather than assuming the mechanical properties of a laminate as defined by the ISO 12215 and associated design assessment methods. Test values for calculations are based on 90 % of the means or the mean minus two standard deviations, whichever value is smaller, and the mean is used for the modulus.	1
Finite Element (FEM)	This method is mainly applicable to "developed" fiber-reinforced plastic construction, and its analysis suggests that structural components are best analyzed using 3D numerical procedures, which are now easily accessible. Design pressure and design stress or strain are determined using ISO 12215.	1

The mechanical properties of the materials may be derived from the relevant content.

The values in Table 3 indicate that the manufacturing-quality factor compensates for higher fabrication qualities and manufacturing processes, and penalizes general methods, such as the hand lay-up method, and low quality. This factor is suggested because the fabrication quality of a laminate may have a significant impact on the mechanical properties of its composite materials. The mechanical properties of composites are significantly affected by the Gc. However, advanced manufacturing methods such as infusion and vacuum-assisted resin transfer molding, which can reduce voids, resin-poor regions, and other defects, are preferred because the composite mechanical properties can be further improved, unlike in the hand lay-up method (Abdurohman et al., 2018; Choi et al., 2013; Heckadka et al., 2015; Kim et al., 2014; Mouritz, 2000).

As depicted in Figure 3, ISO 12215 (2019) considers the “assessment method factor” for FRP hull laminate scantling. It also recommends applying the required thickness scantling when determining the mechanical properties of the laminate. This factor “balances” the results from various assessment methods and ensures that simpler assessment methods yield more conservative results than more scientifically developed ones, such as the developed method, FEM, and test method (ISO, 2019). The details of various methods are summarized in Table 3. According to Table 2, a smaller thickness may be attained using advanced methods (ISO, 2019).

5. Case Study

5.1. Structures of GFRP Fishing Vessel

To study the changes in the design of composite structures in detail, a case study was conducted wherein the ISO 12215 (2008) and ISO 12215 (2019), RINA, CCS, KR, LR, KOMSA, and China MSA were applied to one type of ship. The target ship for this case study was a 40 t E-glass FRP fishing vessel with a length of 20 m, which was designed and constructed according to the KOMSA rules. The laminate design results of its hull structure were ana`lyzed; the material and lamination schedules are listed in Table 5. Here, 450-g/m^2 CSM and 570-g/m^2 WR were used as reinforcements, and the resin used was a polyester. The lamination schedule of external plates, including the bottom plate, was a total of 10 ply of ‘CSM + (CSM + WR) × 4 + CSM,’ and the lamination thickness was 9.14 mm, which included a 6.5 % margin with respect to the required thickness. The mean Gc of the laminate was 0.367. Figure 5 illustrates the structural arrangement of the case study ship and the lamination schedule of the laminate.

Table 4. Principal dimensions of the target ship.

Item	Value	Unit	Item	Value	Unit
Length overall (L_{OA})	19.10	m	Length of waterline (L)	14.066	m
Beam (B)	4.38	m	Gross tonnage (GT)	9.77	t
Depth (D)	1.18	m	Displacement (Δ)	39.39	t
Draft (T)	0.80	m	Service speed (V)	13	knot

Table 5. Material and lamination schedules for hull constructions

		Item	Value	Unit
Material	E-glass fabric	Fabric type 1 (CSM)	450	g/m^2
		Fabric type 2 (WR)	570	g/m^2
	Resin	Polyester resin	-	
Laminate schedule		CSM + (CSM + WR) × 4 + CSM (T_{Design} = 9.14 mm; T_{Req} = 8.58 mm; 10 ply; Mean Gc = 0.367)		

T_{Design}, design thickness; T_{Req}, required thickness.

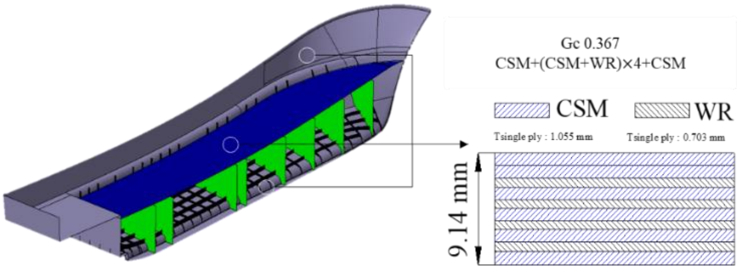


Figure 5. Structural arrangement and laminate stacking schedule of target ship (Han et al., 2021c).

5.2. Redesigning Bottom Plate

The bottom plate, which receives the largest load of the ship structures, was specified as the target component in the case study. Hence, it was redesigned according to each design rule separately. During the redesign process, the hull form and stiffener arrangement were not modified to eliminate the effects of variables other than the estimated mechanical properties of the laminate. To estimate the mechanical properties of the composite, the equations suggested in ISO 12215 (2008, 2019), RINA rule, and design rule were followed. Furthermore, because the fabrication of hull laminates would induce defects, the actual test results were added, and the relevant design results were compared with those specified in ISO 12215 (2019). The flexural test results were used with respect to the changes in Gc and fabric combination implemented in previous studies (Han et al., 2018, 2021c; Oh et al, 2022). Further, the test specimen was designed according to ISO 12215 (2008) and the RINA rule. The material test was conducted according to ASTM D790 (2017) for GFRP hull laminates fabricated using 570-g/m^2 WR cloth, 450-g/m^2 CSM fabric, polyester resin with the hand lay-up method, which is preferred over infusion. The test results regression and rule estimation equation according to each design rule are displayed in Figure 6.

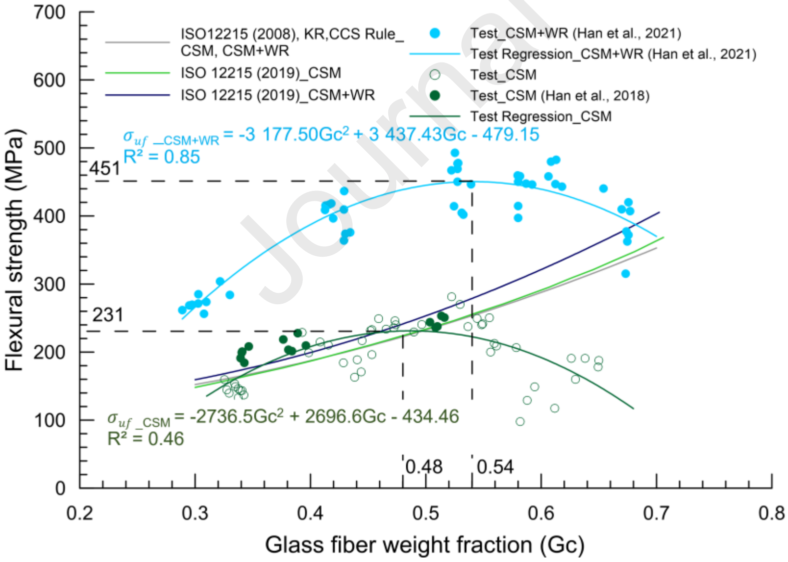


Figure 6. Glass-fiber-reinforced plastic laminate flexural strength suggested in the rules and material test results.

To conduct the case study, a normal Gc and high Gc were selected to determine the Gc. A Gc value of 0.367, which was analyzed using the target ship's specifications, was selected for the normal Gc region. For the high Gc region, the possibility of defects is high during the actual fabrication, and therefore, a relatively high Gc of 0.600 was selected to analyze the difference caused by the boat's manufacturing-quality factor, which was additionally considered in the revised ISO 12215 (2019) standard. Based on the two selected Gc values, the single material type (CSM) and combined material type (CSM + WR) were applied to redesign the hull laminate according to each design rule.

The required thickness was estimated using the equations listed in Table 6, and a thickness margin of 6.5 % was applied to estimate the design thickness (T_{Design}) of the bottom laminate. This margin was selected because the manufacturing thickness of the bottom laminate in the target ship also possessed a 6.5 % margin with respect to the required thickness (Table 5).

Table 6. Equations of required thickness of hull laminates according to seven design rules.

Design rule	Required thickness formulas
ISO 12215 (2019)	$T = s \times Kc \times ((P \times K_{2b}) / (1000 \times 0.5 \times \sigma_{uf}))^{0.5}$
ISO 12215 (2008)	$T = s \times Kc \times ((P \times K_2) / (1000 \times 0.5 \times \sigma_{uf}))^{0.5}$
RINA (2022)	$T_1 = K_1 \times s \times K_a \times P_{0.5} \times (152 / \sigma_{uf})0.5$; $T_2 = 16 \times s \times (152 / \sigma_{uf})^{0.5} \times D^{0.5}$ $T = \mathrm{Max}\ (T_1, T_2)$
KR (2018)	$T = s \times Kc \times ((P \times K_2) / (1000 \times 0.5 \times \sigma_{uf}))^{0.5}$
CCS (2021)	$T = s \times Kc \times ((P \times K_2) / (1000 \times 0.5 \times \sigma_{uf}))^{0.5}$
KOMSA (2021)	$T = 15.80 \times s \times (d + 0.026 \times L)^{0.5}$
Chinese MSA (2019)	$T = 14.63 \times s \times (d + 0.026 \times L)^{0.5}$

s: Short dimension of design area; D: Full load draft (m); L: Full load waterline length (m); P: Design pressure (kN/m^2); σ_{uf}: Flexural strength (MPa); K_c: Curvature correction factor for curved panels; K_1: Coefficient by design pressure type; K_2 and K_a: Panel aspect ratio factor.

Specific E-glass fiber and resin used in laminates were required to estimate the number of raw materials for the laminates. Therefore, the values proposed in the ISO (2008, 2019) standards were employed, wherein the densities of glass fiber and polyester were 2.56 and 1.2 g/cm^3, respectively. Equation (1) was used to determine the laminate weight based on the density of a material proposed in each design rule, and the weight of the laminate was estimated according to these parameters.

$$W_{laminate} = \frac{2.56 \times 1.20 \times T}{2.56 - 1.36 \times Gc} \tag{1}$$

where T is the laminate thickness, here is T_{Design} in mm, Gc is the impregnation rate of the laminate, 2.56 g/cm^3 is the fiber density, 1.20 g/cm^3 is the resin density, and 1.36 is the density difference between fiber and resin.

5.3. Comparison and Discussion

First, the estimation results according to each design rule are summarized in Table 7. In this case study, a planning mode was adopted with the LR rule and a displacement mode was used with all other design rules. Therefore, the conditions were more conservative when estimating the design pressure during operation of a vessel using the LR rule. Hence, for a fair comparison, the LR rule was excluded from the analysis target (Han et al., 2020c). The estimated mechanical properties of the laminate are summarized in Table 8, and the material test results according to Gc is determined by the flexural test results regression equations in Figure 6. The design result of laminates according to each design rule is summarized in Table 9.

Table 7. Design pressure estimation results for hull structure laminate design of target ship

Design rule	Applied mode determination				Design pressure (kN/m^2)
	Definition in each design rule		Target ship		
	Displacement	Planning	$V/L^{0.5}$	Applied mode	
ISO 12215 (2019)	$V/L^{0.5} < 5$	$V/L^{0.5} \geq 5$	$V/L^{0.5} = 3.5$	Displacement	59.49
ISO 12215 (2008)	$V/L^{0.5} < 5$	$V/L^{0.5} \geq 5$		Displacement	59.49
RINA (2022)	$V/L^{0.5} < 4$	$V/L^{0.5} \geq 4$		Displacement	17.91
LR (2021)	$V/L^{0.5} < 3$	$V/L^{0.5} \geq 3$		***Planning***	42.04

KR (2018)	$V/L^{0.5} < 5$	$V/L^{0.5} \geq 5$		Displacement	59.49
CCS (2021)	$V > 10$ kn and $V > 3.7^{0.1667}$ m/s → High-speed vessel			Displacement	45.19
KOMSA (2021)	$V/L^{0.5} < 9$	$V/L^{0.5} \geq 9$		Displacement	-
Chinese MSA (2021)	$V > 10$ kn and $V > 3.7^{0.1667}$ m/s → High-speed vessel			Displacement	-

V, service speed (knot); *L*, length of waterline (m).

Table 8. Flexural strength estimation results for hull laminate design

	ISO 12215 (2008)[a]		ISO 12215 (2019)		Material Test	
Fabric combination	CSM	CSM + WR	CSM	CSM + WR	CSM	CSM + WR
Gc = 0.367	175	175	176	185	187	354
Gc = 0.600	288	288	298	314	192	439

a. Bending strengths according to RINA (2022), KR (2018), and CCS (2021) are identical to that of ISO 12215 (2008).

b. KOMSA and China MSA do not suggest a mechanical property estimation formula but require minimum values.

Table 9. Hull laminate design results according to each design rule

	Required thickness (mm)		Weight (kg/m²)[a]		Required thickness (mm)		Weight (kg/m²)[a]	
Design Gc	Normal Gc = 0.367				High Gc = 0.600			
Fabric combination	CSM	CSM + WR	CSM	CSM + WR	CSM	CSM + WR	CSM	CSM + WR
ISO 12215 (2019)	7.35	6.83	11.67	10.84	5.65	5.35	10.60	10.04
ISO 12215 (2008)	7.64	7.64	12.13	12.13	5.95	5.95	11.16	11.16
RINA (2022)	8.03	8.03	12.75	12.75	6.33	6.33	11.87	11.87
KR (2018)	7.64	7.64	12.13	12.13	5.95	5.95	11.16	11.16
CCS (2021)	8.23	8.23	13.07	13.07	6.42	6.42	12.04	12.04
KOMSA (2021)	8.58	8.58	13.62	13.62	8.58	8.58	13.62	13.62
China MSA (2019)	7.94	7.94	12.60	12.60	7.94	7.94	12.60	12.60

a. Laminate weight per unit area was calculated using design thickness added 6.5 % margin to required thickness.

The design results can be approximately categorized into three groups. First, the design results according to ISO 12215 (2008) and the RINA, KR, and CCS rules, which consider the Gc effect on laminate thickness and weight, were identical regardless of fabric combination. Second, the design results according to domestic rules, such as KOMSA and China MSA, had identical estimation results regardless of fabric combination and the changes in Gc. The impact of fabric combination and Gc on the laminate strength was not reflected, and a safety margin was uniformly applied. Third, the design results according to the revised ISO 12215 (2019) reflected the effects of fabric combination, in addition to Gc, which was considered in ISO 12215 (2008). From the results, it is confirmed that laminate with high Gc and combined fabric is thinner than that with normal Gc and single material.

Furthermore, the design results according to ISO 12215 (2008) were compared with those according to ISO 12215 (2019), as illustrated in Figure 7. Consequently, the effects of the design results according to the revised ISO 12215 (2019) can be intuitively confirmed.

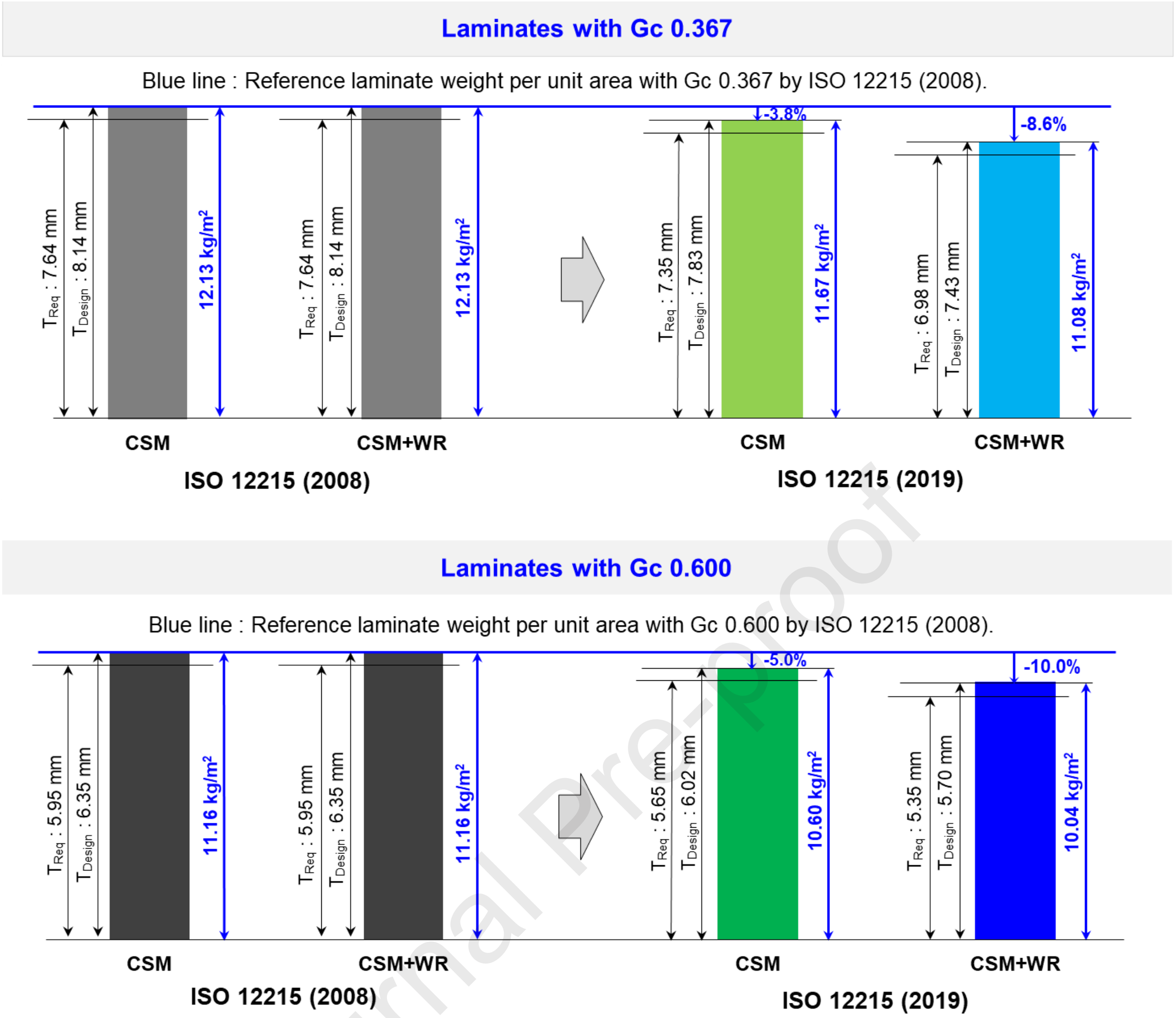


Figure 7. Comparison of laminate design results according to ISO 12215 (2008, 2019).

As indicated in Figure 7, compared with the design results according to ISO 12215 (2008), those according to the revised ISO 12215 (2019) demonstrated a tendency toward reduced weight in the two fabric combination cases (single and combined materials) of the normal Gc (0.367) and high Gc (0.600). In particular, stronger effects of weight reduction were observed in the combined material case (both normal and high Gc). As demonstrated by the results of the estimation of flexural strength in Figure 6 and Table 8, the effects of fabric combination on the mechanical properties of laminate estimation are reflected in the revised ISO 12215 (2019); particularly, the flexural strength was suggested to be in the range 10–26 MPa, which is higher than that specified in ISO 12215 (2008) for the CSM and WR combination. Additionally, the adjustment factor for the design area size was revised to be smaller in ISO 12215 (2019) than in the 2008 version. In general, the effect of weight reduction is reflected by raw material reduction, improved material usage efficiency, and reduction in fabrication costs. Furthermore, hull weight reduction has a direct positive impact in terms of improved operational efficiency of the ship, reduction of greenhouse gas emissions, and reduced environmental loads generated when fabricating and discarding raw materials (Han et al. 2020c; Jeong et al., 2020; Oh et al., 2019).

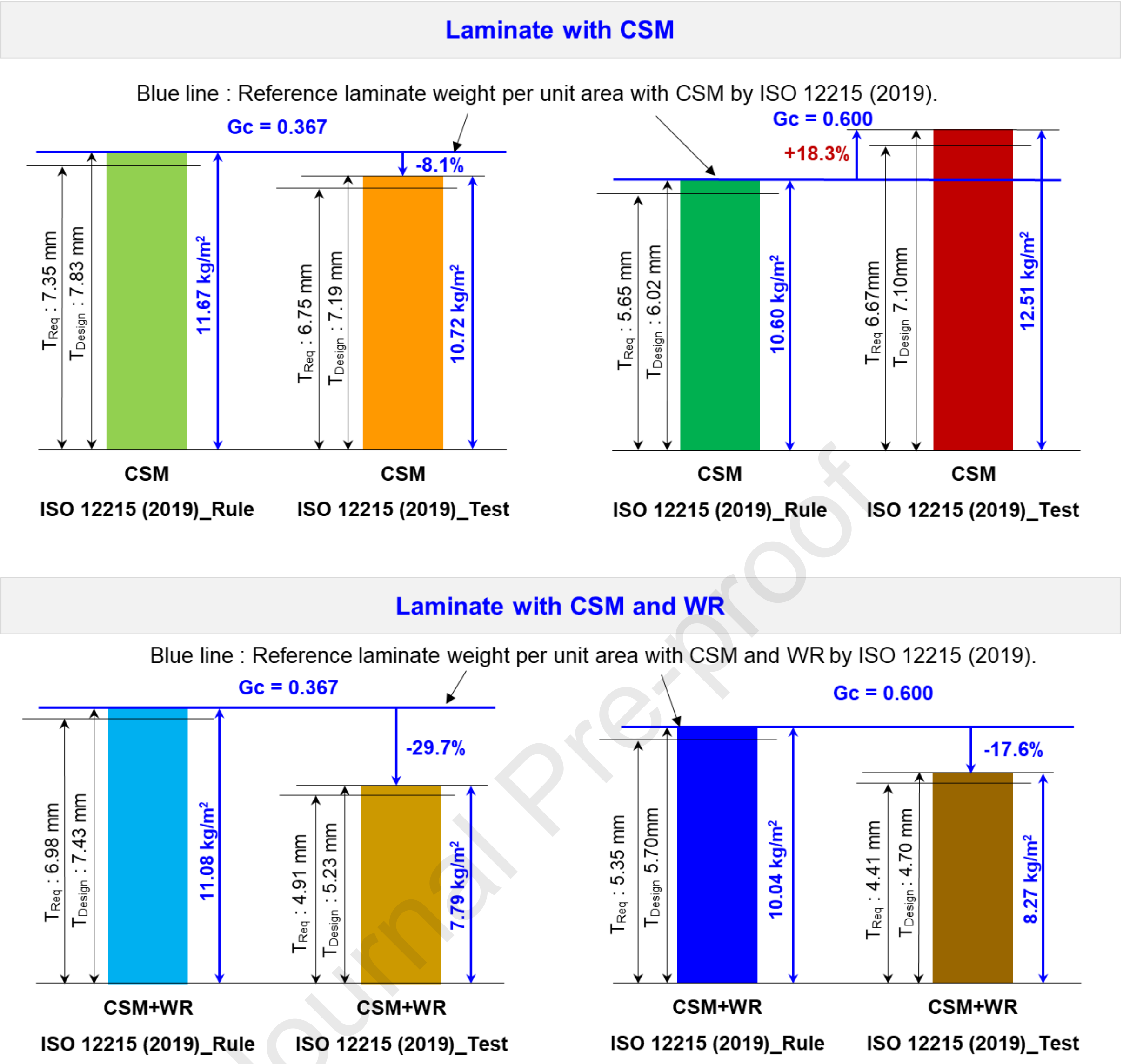


Figure 8. Comparison of laminate design results according to ISO 12215 (2019) and material test results.

The analysis of the revised ISO 12215 (2019) revealed that, for a normal Gc (0.367), the laminate design results according to flexural test results had a higher possibility of reducing weight than those according to ISO 12215 (2019), and the CSM and WR combination could have higher strength than the CSM single material, allowing it to be thinner than the latter. As illustrated in Figure 8, the flexural-strength test results are better. In contrast, the laminate design results according to ISO 12215 (2019) have a more suitable flexural-strength safety margin for weight reduction than the actual test results.

However, the tendencies of a high Gc (0.600) were different to those of a normal Gc (0.367). For combined CSM and WR, the Gc according to ISO 12215 (2019) can reduce more weight than that of the actual test case. However, the possibility is smaller than that with the normal Gc. The outcomes of the design of CSM according to ISO 12215 (2019) indicated the possibility of a safety issue. The reason for this can be interpreted from the comparison chart of flexural strength and the test results (Figure 6): the test results improve at first, and subsequently start to degrade. CSM deteriorates more than the CSM + WR composite and does not satisfy the flexural strength value suggested in the ISO standard for Gc = 0.50. The reason for the deterioration in the high-Gc region is that the material contained more intrinsic defects, such as void and delamination, than that in the low-Gc region (Han et al., 2021c; Lee et al., 2021; Oh et al., 2020). Furthermore, more defects were observed in the CSM single material than in the CSM + WR composite. Application of the manufacturing-quality factor in the estimation of mechanical properties is recommended in ISO 12215 (2019), albeit uniformly regardless of changes in the Gc. Therefore, the effect of the fabrication method as well as material design conditions such as Gc on the fabrication quality must be considered.

6. Conclusions

To analyze the design trend of the composite hull structure, this study reviewed the recent revisions to the ISO standards of composite material design for ship hulls were reviewed and compared with the recommendations in related classification society rules. According to the analysis, the current design trend of composite structures is to prioritize the effects of design variables, such as fabric combination and fabrication method, on the mechanical properties of laminates, which were confirmed through a case study in this review.

In ISO 12215 (2019), the process of determination of the mechanical properties of a laminate related to the material design of a composite hull structure is defined in a more segmented manner. The fabric type and combination are additionally reflected in the mechanical properties of the laminate with respect to different Gc, and the quality weight according to the fabrication method is also recommended. Thus, it recommends better mechanical properties for the laminate than those in ISO 12215 (2008). Considering these factors, under the same ship-design conditions, the hull structure designed according to ISO 12215 (2019) is lighter than that designed according to the previous version, which results in better operational efficiency and reduced environmental loads.

The new ISO 12215 considers the effect of fabrication methods on the composite's mechanical properties. However, the impact of Gc and the changes in the fabric combination on the manufacturing quality are not reflected in the estimation of the composite's mechanical properties. Thus, in the high-Gc region, the design results for CSM according to ISO 12215 (2019) may engender safety issues. In contrast, the results of tests performed by researchers who considered additional design variables did not produce safety concerns. In other words, the effects of design variables, such as Gc and fabric combination, on the manufacturing quality must be considered during the estimation of the composite's mechanical properties.

In certain classification society rules, such as RINA, KR, and CCS, which are based on ISO 12215 (2008), the glass fabric type (such as CSM and WR) is not specified when recommending the mechanical properties of the laminate. Further, the effect of the fabrication method is not considered when estimating the mechanical properties. Domestic rules such as those of the KOMSA and China MSA also do not suggest the mechanical properties of the laminate with respect to the changes in Gc. However, numerous studies have indicated that design variables, such as Gc, fabric type, and fabric combination, have considerable influences on the mechanical properties. The design rules of classification societies and domestic agencies are also expected to be revised, as stated in ISO 12215, to incorporate more variables and subsequently cater to international standard revision trends.

These findings provide novel insights into the structural design of composite hulls and may be used to support further regulatory developments to achieve safe, reliable, lightweight, and sustainable vessels. Moreover, future developments of the ISO 12215 are motivated by the need to improve sustainability through the choice of materials; therefore, consideration of Gc and the properties of new, sustainable composite materials are essential. Further study should focus on controlling the design bending moment factor, the validity of which is currently limited. Additionally, other fabric type and its' combination, such as unidirectional and quadriaxial glass fabric, etc., used in hull structure may also be further studied in future.

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References

Abdurohman, K., Satrio, T., Muzayadah, N.L., Teten, 2018. A comparison process between hand lay-up, vacuum infusion and vacuum bagging method toward e-glass EW 185/lycal composites. J. Phys. Conf. Series 1130, 012018. https://doi.org/10.1088/1742-6596/1130/1/012018.

ASTM D790, 2017. Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. ASTM International: West Conshohocken, PA, USA.

Barsotti, B., Gaiotti, M., Rizzo, C.M., 2020. Recent industrial developments of marine composites limit states and design approaches on strength. J. Marine. Sci. Appl. 19, 553–566. https://doi.org/10.1007/s11804-020-00171-1.

Bhat, R., Mohan, N., Sharma, S., Pratap, A., Keni, A.P., Sodani, D., 2019. Mechanical testing and microstructure characterization of glass fiber reinforced isophthalic polyester composites. J. Mater. Res. Technol. 8, 3655–3661. https://doi.org/10.1016/j.jmrt.2019.06.003.

Chandel, P.S., Tyagi, Y.K., Jha, K., Kumar, R., Sharma, S., Singh, J., Ilyas, R.A., 2021. Study of mode II interlaminar fracture toughness of laminated composites of glass and jute fibres in epoxy for structural applications. Funct. Compos. Struct. 3, 044002. https://doi.org/10.1088/2631-6331/ac376e.

China Classification Society (CCS), 2019. Rules for Construction and Classification of Yachts; CCS, Beijing, China.

China Maritime Safety Administration (MSA), 2019. Guideline for GFRP Fishing Vessel Construction. China MSA: Beijing, China.

Cho, S.-Y., Lee, J.-R., 2021. Investigation of manufacturing defects in 3D-printed CFRP using laser ultrasonic testing and x-ray micro-computed tomography. Funct. Compos. Struct. 3, 025005. https://doi.org/10.1088/2631-6331/ac034d.

Choi, H.-K., Nam, K.-W., Aha, S.-H., 2013. Strength characteristics of FRP composite materials for ship structure. J. Ocean Eng. Technol. 27, 45–54. https://doi.org/10.5574/KSOE.2013.27.4.045.

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M.L.D., Pauly, D., 2019. Global trends in carbon dioxide (CO_2) emissions from fuel combustion in marine fisheries from 1950 to 2016. Mar. Policy 107, 103382. https://doi.org/10.1016/j.marpol.2018.12.001.

Han, Z., Choi, J.K., Hwang, I., Kim, J., Oh, D., 2020b. Basic design of high-speed riverine craft made of carbon fiber reinforced polymer. J. Soc. Nav. Archit. Korea. 57, 241–253. https://doi.org/10.3744/SNAK.2020.57.4.241.

Han, Z., Jang, J., Lee, S.-G., Lee, D., Oh, D., 2021a. Error analysis of non-destructive ultrasonic testing of glass fiber-reinforced polymer hull plates. J. Compos. Sci. 5, 238. https://doi.org/10.3390/jcs5090238.

Han, Z., Jeong, S., Jang, J.-W., Woo, J.H., Oh, D., 2021b. Ultrasonic attenuation characteristics of glass-fiber-reinforced polymer hull structure. Appl. Sci. 11, 6614. https://doi.org/10.3390/app11146614.

Han, Z., Jeong, S., Noh, J., Oh, D., 2020a. Comparative study of glass fiber content measurement methods for inspecting fabrication quality of composite ship structures. Appl. Sci. 10, 5130. https://doi.org/10.3390/app10155130.

Han, Z.Q., Jang, J.W., Lee, K.Y., Oh, D.K., 2021c. Lightweight-laminate design of fishing boat considering mechanical properties of glass fiber reinforced polymer. Shipbuild. China 62, 132–144.

Han, Z.Q., Jang, J.W., Noh, J., Oh, D., 2018. A study on material properties of FRP laminates for a composite fishing vessel's hull. Proc. 2018 Spring Conf. Korean Soc. Precis. Eng., Jeju, South Korea.

Han, Z.Q., Jang, J.W., Oh, D.K., 2020c. Design margin of composite structures of Korean fishing vessel and assessment of its environmental impact. Shipbuild. China 61, 90–100.

Heckadka, S.S., Nayak, S.Y., Narang, K., Pant, K.V., 2015. Chopped strand/plain weave E-glass as reinforcement in vacuum bagged epoxy composites. J. Mater. 2015, 957043. https://doi.org/10.1155/2015/957043.

ISO (International Organization for Standardization), 2008. ISO 12215-5: Small Craft—Hull Construction, and Scantlings—Part 5: Design Pressures for Monohulls, Design Stresses, Scantlings Determination; ISO: Geneva, Switzerland.

ISO (International Organization for Standardization), 2019. ISO 12215-5: Small Craft—Hull Construction, and Scantlings—Part 5: Design Pressures for Monohulls, Design Stresses, Scantlings Determination; ISO: Geneva, Switzerland.

Jang, J.-W., Han, Z.Q., Oh, D.K., 2019. Light-weight optimum design of laminate structures of a GFRP fishing vessel. J. Ocean Eng. Technol. 33, 495–503. https://doi.org/10.26748/KSOE.2019.105.

Jeong, S.H., Woo, J.H., Oh, D.K., 2020. Simulation of greenhouse gas emissions of small ships considering operating conditions for environmental performance evaluation. Int. J. Nav. Archit. Ocean Eng. 12, 636–643. https://doi.org/10.1016/j.ijnaoe.2020.07.006.

Kim, E., Jung, D., Yu, W.-R., Na, W., 2022. Influence of water absorption on the mechanical behavior of CFRPs manufactured by RTM at room temperature. Funct. Compos. Struct. 4, 015007. https://doi.org/10.1088/2631-6331/ac5a5f.

Kim, S.-H., Kim, C.-G., 2008. Optimal design of composite stiffened panel with cohesive elements using micro-genetic algorithm. J. Compos. Mater. 42, 2259–2273. https://doi.org/10.1177/0021998308094967.

Kim, S.Y., Shim, C.S., Sturtevant, C., Kim, D., Song, H.C., 2014. Mechanical properties and production quality of hand-layup and vacuum infusion processed hybrid composite materials for GFRP marine structures. Int. J. Naval Archit. Ocean Eng. 6, 723–36. https://doi.org/10.2478/IJNAOE-2013-0208.

Korea Maritime Transportation Safety Authority (KOMSA), 2021. Standard of Construction and Equipment for the Less Than 10 Gross Tonnage of Small Fishing Vessels; KOMSA: Sejong, South Korea.

Korean Register (KR), 2018. Guidance for Recreational Crafts; KR, Busan, South Korea.

Kulhan, T., Kamboj, A., Gupta, N.K., Somani, N., 2022. Fabrication methods of glass fibre composites—A review. Funct. Compos. Struct. 4, 022001. https://doi.org/10.1088/2631-6331/ac6411.

Lee, J., Soutis, C., 2005. Thickness effect on the compressive strength of T800/924C carbon fiber–epoxy laminates. Compos. Part A: Appl. Sci. Manuf. 36, 213–227. https://doi.org/10.1016/j.compositesa.2004.06.010.

Lee, S.-G., Oh, D., Woo, J.H., 2021. The effect of high glass fiber content and reinforcement combination on pulse-echo ultrasonic measurement of composite ship structures. J. Mar. Sci. Eng. 9, 379. https://doi.org/10.3390/jmse9040379.

Lloyd's Register (LR), 2021. Rule and Regulations for the Classification of Special Service Crafts; LR, London, UK.

Lorimer, T., Allen, T., 2022. Concurrent Multi-Component Optimization of Stiffened-Plate Yacht Structures. J Sailing Technol. 7, 203–227. https://doi.org/10.5957/jst/2022.7.10.203.

Luan, C., Movva, S., Wang, K., Yao, X., Zhang, C., Wang, B., 2019. Towards next-generation fiber-reinforced polymer composites: A perspective on multifunctionality. Funct. Compos. Struct. 1, 042002. https://doi.org/10.1088/2631-6331/ab47f9.

Mariatti, M., Chum, P.K., 2005. Effect of laminate configuration on the properties of glass fiber-reinforced plastics (GFRPs) mixed composites. J. Reinf. Plast. Compos. 24, 1713–1721. https://doi.org/10.1177/0731684405051654.

Mouritz, A.P., 2000. Ultrasonic and interlaminar properties of highly porous composites. J. Compos. Mater. 2000, 34, 218–39. https://doi.org/10.1177/002199830003400303.

Oh, D., Jang, J., Jee, J.H., Kwon, Y., Im, S., Han, Z., 2022. Effects of fabric combinations on the quality of glass fiber reinforced polymer hull structures. Int. J. Nav. Archit. Ocean Eng. 14, 100462. https://doi.org/10.1016/j.ijnaoe.2022.100462.

Oh, D.K., Han, Z.Q., Noh, J.K., 2018. Light-weight design of 11 m-CFRP high speed craft using laminates weight optimization method for composite ship structures. Mar. Technol. 5, 77–84.

Oh, D.K., Han, Z.Q., Noh, J.K., Jeong, S.H., 2020. Laminate weight optimization of composite ship structures based on experimental data. J. Soc. Nav. Archit. Korea. 57, 104–113. https://doi.org/10.3744/SNAK.2020.57.2.104.

Oh, D.-K., Lee, D.-K. Kang, G.-M., Ryu, C.-H., Noh, J., 2014. Comparative study of rules of ISO 12215 and international classification society for structural design of CFRP cruise boat. J. Ocean Eng. Technol. 28, 77–84. https://doi.org/10.5574/KSOE.2014.28.1.077.

Oh, D.K., Lee, D.K., Jeong, S.H., 2019. Environmental impact evaluation on lightweight structure design of a composite ship by LCA (life cycle assessment). J. Korean Soc. Precis. Eng. 36, 875–881. https://doi.org/10.7736/KSPE.2019.36.9.875.

Rashid, B., Sadeq, A., Ebraheem, M., Mohammed, A.R., 2019. Mechanical properties of hybrid woven roving and chopped strand mat glass fabric reinforced polyester composites. Mater. Res. Express 6, 105208. https://doi.org/10.1088/2053-1591/ab4085.

Registro Italiano Navale (RINA), 2022. Rules for the Classification of Pleasure Yacht Part B Hull and Stability; RINA, Genova, Italy.

Satheesh, R., Narayanaa Naik, G., Ganguli, R., 2010. Conservative design optimization of laminated composite structures using genetic algorithms and multiple failure criteria. J. Compos. Mater. 2010, 44, 369–387. https://doi.org/10.1177/0021998309347579.

Scott, R.J., 1996. Fiberglass Boat Design and Construction, second ed. The Society of Naval Architects and Marine Engineers: Jersey City.

Song, J.H., Oh, D.K. Lightweight Structure Design for Composite Yacht with Optimum Fiber Mass Content. In Proc. Int. SAMPE Symp. Exhibit. Long Beach, CA, USA. 25 May 2016.

Souppez, J.R., Laci, J., 2022. Ultimate Strength of Quasi-Isotropic Composites: ISO 12215-5:2019 Validation. Int. J. Marit. Eng. 164, 237-246. https://doi.org/10.5750/ijme.v164iA2.1178.

Srivastava, S.K., Singh, I.P., 2007. Effect of laminate configurations on impact properties of GFRP composite in seawater. Appl. Mech. Mater. 7–8, 223–227. https://doi.org/10.4028/www.scientific.net/AMM.7-8.223.

Stenius, I., Rosén, A., Kuttenkeuler, J., 2011. On structural design of energy efficient small high-speed craft. Mar. Struct. 24, 43–59. https://doi.org/10.1016/j.marstruc.2011.01.001.

Tawfik, B. E., Leheta, H., Elhewy, A., Elsayed, T.,2017. Weight reduction and strengthening of marine hatch covers by using composite materials. Int. J. Nav. Archit. Ocean Eng. 9, 185–198

Tuswan, T., Abdullah, K., Zubaydi, A., Budipriyanto, A., 2019. Finite-element analysis for structural strength assessment of marine sandwich material on ship side-shell structure. Mater. Today Proc. 13, 109–114. https://doi.org/10.1016/j.matpr.2019.03.197.

Ujianto, O., Nugroho, A., Setijotomo, H.S., Bintoro, A., 2020. Effect of fabrication techniques, resin types and fiber combinations on mechanical properties and morphology of glass fiber composites. Int. J. Mater. Mech. Manuf. 8, 17–21. https://doi.org/10.18178/ijmmm.2020.8.1.477.

Yum, J.S., Yoo, J.H., 2016. Structural strength assessment and optimization for 20 feet class power boat. J. Soc. Nav. Archit. Korea. 53, 108–114. https://doi.org/10.3744/SNAK.2016.53.2.108.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: