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Basic Design of High-Speed Riverine Craft Made of Carbon Fiber Reinforced Polymer

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The Small-Unit Riverine Craft (SURC) is a small high-speed vessel used by navies and marine corps in relatively shallow waterway environments, such as riverine areas or littoral coasts. In the past, SURCs have primarily been rigid-hulled inflatable boats constructed using composite materials such as glass fiber reinforced plastics. More recently, single-hull SURCs have been manufactured using aluminum for weight reduction. In this study, a Carbon Fiber Reinforced Polymer (CFRP) material was applied instead to examine its feasibility in the basic design of an SURC with a hull length of 10 m. The CFRP structural design was obtained using the properties of a marine CFRP laminate, determined in a previous study. Next, the designed CFRP SURC was modeled to confirm its functionality, then compared with existing aluminum SURCs, indicating that the CFRP SURC was 41.49 % lighter, reduced fuel consumption by 30 %, and could sail 50 NM further for every hour of engine operation. A method for reducing the high cost of carbon fiber was also proposed based on the adjustment of the carbon fiber content to provide the optimum strength where required. The data developed in this study can be used as a basis for further design of CFRP craft.

Keywords : Carbon fiber, CFRP(Carbon Fiber Reinforced Polymer), Small craft, Composite ship, High-Speed craft

1. Introduction

The Small-Unit Riverine Craft (SURC) is a small high-speed rigid-hull, armed and armored patrol craft operated by a Navy or Marine Corps in relatively shallow water channel environments such as riverine areas or littoral coasts. The main purpose of the SURC is to provide patrol missions with tactical mobility, primarily in maritime operations, and to provide a weapons platform that can provide limited support to ground combat forces. The SURC also performs logistic, resupply, and noncombatant evacuation or humanitarian assistance as well as command, control, and reconnaissance operations in these littoral and riverine environments.

The special purpose SURC for military operation in a riverine environment has a displacement of approximately 5-10 tons, and, by adopting a waterjet propeller, can secure a maximum speed of 40-45 knots while maintaining maneuverability in shallow water depths and complex waterway environments. The hulls of such SURCs are primarily made of aluminum or composite materials such as Glass Fiber Reinforced Polymer (GFRP) (Lee et al., 2011). Fig. 1 shows examples of SURCs built of aluminum.

Carbon Fiber Reinforced Polymer (CFRP) is a new marine composite material that has been applied to the development of luxury yachts, racing yachts, and other special purpose vessels. However, the cost of CFRP remains very high, and there are few CFRP-based ships that can be used as a design reference, unlike in the aviation or automobile sectors, in which CFRP has been extensively used. Furthermore, as CFRP-based ships are usually built for special purposes, design data are often not disclosed. Finally, because CFRP

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is still a new material when applied in hulls, the accompanying structure design remains somewhat challenging. The ISO 12215 (ISO, 2019), specifications, which govern the design and construction of small craft, covers the design of CFRP hull structures along with the requirements for using carbon fiber as the hull material. Several international classification societies recommend design and construction specifications for CFRP structures based on this ISO standard, or provide their own, more advanced specifications. However, in Korea, specifications regarding small vessels have yet to be established.

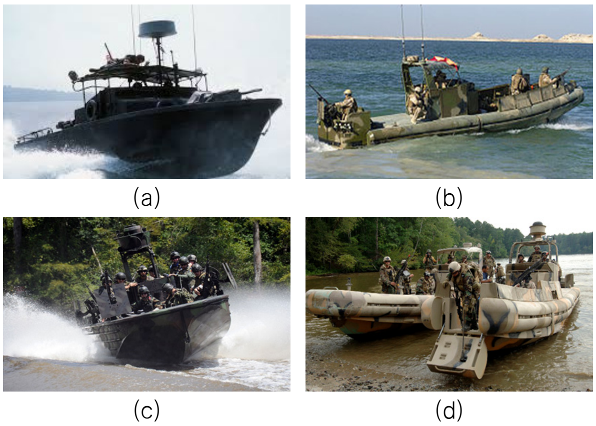

(a) (b) (c) (d)

Fig. 1 High-speed Small-Unit Riverine Crafts (SURCs): (a) Patrol boat riverine (Military Factory, 2020), (b) US Navy riverine squadron patrol craft (United States Navy, 2020a), (c) Special operational craft–riverine (United States Navy, 2020b), (d) Small-Unit Riverine Craft (United States Navy, 2020c)

To apply CFRP in the hull of a small craft, the authors previously comparatively analyzed the structural design procedures contained in the ISO standards and related classification rules (Oh et al., 2014) and developed several CFRP vessels (Oh et al., 2015; Oh et al., 2019b). Furthermore, material tests have been conducted on a CFRP laminate intended for use in boat hulls (Kang et al., 2014; Oh et al., 2019a). In this study, an SURC is developed using CFRP based on the results of these previous studies. First, a feasibility study was conducted to analyze the characteristics and essential requirements of an existing aluminum SURC, the results of which were used to design the CFRP hull of the proposed SURC. To this end, hull forms and structures well-suited to the properties of CFRP materials were developed, and a Digital Mock-Up (DMU) model including the propulsion system and cabin house was constructed. Then, an approach was developed for the optimization of the proposed CFRP SURC. Finally, the design results of the developed CFRP SURC were evaluated through comparison with previous research and a conventional aluminum SURC, and the optimization of the proposed CFRP SURC was analyzed.

2. Specifications of proposed CFRP SURC

A CFRP high-speed SURC should be designed with consideration of the required geometrical characteristics as well as the characteristics of the CFRP material. According to Oh et al. (2013), Jeong et al. (2014), Kim et al. (2014), and Oh et al. (2014), a CFRP high-speed craft should have a sharp cross-section, such as deep-v shape or concave shape, and due to the reduced weight of the CFRP hull, the superstructure must be smaller than that of a traditional GFRP craft. Fig. 2 shows examples of several different special high-speed craft made of CFRP.

In this section, the main functions and dimensions of similar SURCs are analyzed and the requirements of the ship design are defined. Based on these definitions, data from similar CFRP high-speed craft are then analyzed to define the principal particulars and hull shapes that constitute the two main design specifications.

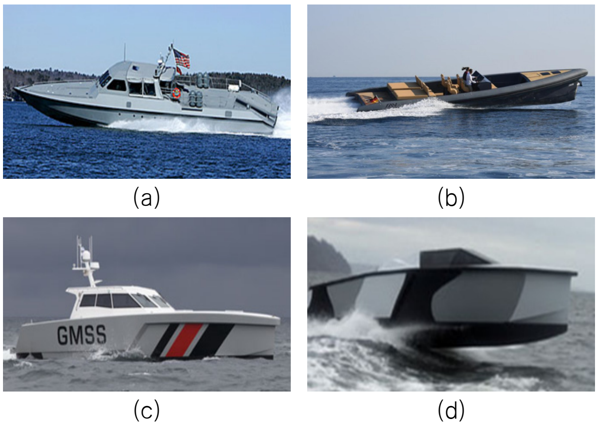

(a) (b) (c) (d)

Fig. 2 CFRP high speed special craft: (a) Coastal patrol boat (Hodgdon Defense Composites, 2020), (b) High speed inflatable boat (SAY Carbon, 2020), (c) Long range patrol craft (Zyvex Marine, 2020a), (d) Unmanned surface vessel (Zyvex Marine, 2020b)

2.1 SURC features and design requirements

A summary of the trends and main characteristics (Lee et al., 2011) of ships similar to SURCs that are operated in Korea and other countries is provided as follows. Most SURC-like ships are of the Rigid-hulled Inflatable Boat (RIB) type, but recently, as the number of required armaments and electronic equipment increases, the trend is to build a single-hull type craft. In terms of displacement, most SURC-like ships have been built at a small scale of 2 to 3 tons, though recently they have been constructed as high as about 5 to 10 tons, or even around 20 tons. Most propellers adopt a diesel engine waterjet propulsion system. The cruising speed of these craft is 30–35 knots with a maximum speed in the range of 40–45 knots. The operating range at cruising speed varies from a minimum of 120 NM to a maximum of 500 NM, with most around 200–300 NM. When utilized by armed forces, these craft are typically equipped with a minimum number of machine guns for self-defense, though recently, there has been a tendency to equipped such vessels with Gatling guns or small mines as well. The electronic systems usually consist of equipment for underwater navigation as well as navigational radar and advanced equipment such as wireless communication systems.

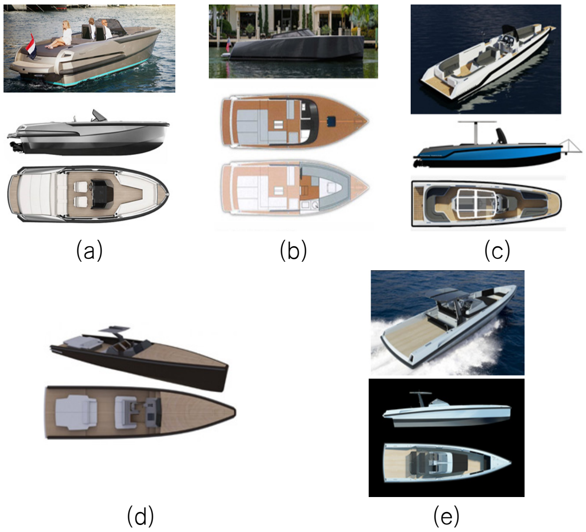
Typically, GFRP is used as the hull material, as described in Section 1. As a result, the quantity of mounted equipment has been increasing, so aluminum has been often applied instead of GFRP to improve vessel mobility. In particular, the major river areas in Korea possess narrow passages connecting their inland stretches to the sea with an average depth of 1–5 m. Furthermore, there are many obstacles such as sandbars in these passages. Therefore, it is reasonable to suppose that a single-hull type craft with a shallow draft and moderate deadrise would be desirable for application in Korea.

The requirements of the CFRP SURC designed in this study can be summarized based on the desired characteristics of the proposed SURC: it should accommodate one squad or eight people; the hull length, L_H, should be approximately 10 m; and the maximum speed should be 40–50 knots, which is faster than most existing SURCs considering the potential weight reduction realized by using CFRP.

Furthermore, according to the operational concept of the SURC and the specific conditions of the intended operation area, the following geometric features were considered. First of all, considering the special characteristics of Korea's major rivers and coastal areas, a draft of 1 m or less was ensured. Second, considering the need for mobility and performance, a waterjet was adopted for propulsion. Third, to provide quick berthing and maneuvering, a ramp was installed at the head of the boat, and a standing seat and open helm station were included in the design so that the crew could be seated stably and move quickly during operations. Fourth, the need for bulletproof armor was considered in the design. Finally, space was provided for appropriate armaments.

2.2 Principal dimensions

The detailed design information of 12 existing CFRP high-speed craft that meet the basic requirements of the CFRP SURC defined in the previous section were investigated, among which five similar ships with similar hull lengths and performance conditions, shown in Fig. 3, were analyzed in detail.


(a) (b) (c)

(d) (e)

Fig. 3 Similar CFRP high-speed craft: (a) Ribbon R27 (Ribbon Yachts, 2020), (b) VanDutch 30 (VanDutch, 2020), (c) Beach lander (Allure Marine, 2020), (d) C-12M (C-boat, 2020), (e) Wally tender (Wally, 2020)

In the analysis of similar ships, the dimensions and weights were statistically processed according to the definitions in ISO 8666 (ISO, 2016) and ISO 12217 (ISO, 2015) to estimate the principal particulars of the CRFP SURC using the small craft design tool presented by Oh & Lee (2017).

Table 1 shows the main specifications of the similar ships that were used in the design tool, and Fig. 4 provides a summary of changes in these major items according to changes in the hull length, L_H. Table 2 shows the principal dimensions suitable for a hull length of 10 m, as initially defined. According to ISO 12217, additional loading conditions have to be determined to check buoyancy and stability. This was accomplished using the design tool proposed by Oh & Lee (2017), and the results are discussed in conjunction with the waterjet selection in Section 2.3.

Table 1 Principal particulars of similar CFRP ships

Craft	CFRP-I	CFRP-II	CFRP-III	CFRP-IV	CFRP-V
L_H (m)	8.36	9.56	10.30	12.30	13.60
B_H (m)	2.55	2.80	3.00	3.66	4.30
$D_{LWL/2}$ (m)	1.56	2.10	1.30	1.45	1.60
T (m)	0.41	0.80	0.40	0.50	0.60
m_{LCC} (ton) (w/o engine)	1.13	2.69	2.24	2.10	3.85
m_{LDC} (ton)	2.30	4.50	4.80	4.00	6.50

L_H : The length of the hull
B_H : The beam of the hull
$D_{LWL/2}$: The midship depth
T : The draft
m_{LCC} : The light craft mass
m_{LDC} : The loaded displacement mass

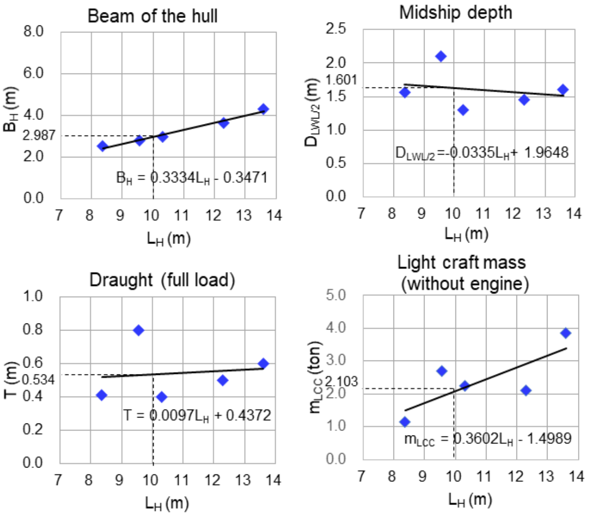


Fig. 4 Changes in principal dimensions according to the change in L_H

Table 2 Principal particulars of the design ship

Items	Value
L_H (m)	10.000
B_H (m)	2.987
$D_{LWL/2}$ (m)	1.601
T (m)	0.514
m_{LCC} (ton) (w/o engine)	2.103

To design the hull form, CFRP-V, which has the most similar dimensions to the selected design parameters among the evaluated ships, was selected as the template ship, based on which the hull form of the proposed CFRP SURC was designed, such that L_{WL} was defined as 90 % of L_H, B_{WL} as 95 % of B_H, and T as 0.514 m. In this design, the estimated value from the design tool was 5.404 ton for m_{LDC}, which represents the fully loaded displacement. The process of obtaining these values is discussed in detail in Section 3. Based on the hull form of CFRP-V, the Maxsurf modeler (Bentley, 2020) was used to obtain the hull form of the proposed CFRP SURC as shown in Fig. 5, and the principal particulars of this hull are shown in Table 3.

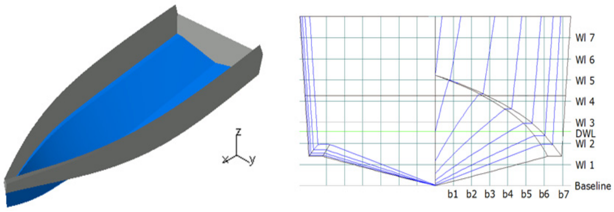


Fig. 5 Hull form of the design ship

Table 3 Principal particulars of design ship

Items	Value
L_H (m)	10.000
L_{WL} (m)	9.000
B_H (m)	2.987
B_{WL} (m)	2.823
$D_{LWL/2}$ (m)	1.601
T(m)	0.514
C_B	0.404
C_P	0.578
β (Deadrise at 0.5L_{WL}, deg)	20.100
L_{CB} (from AP, %L_{WL})	32.593
m_{LDC} (ton)	5.404

2.3 Waterjet selection and weight estimation

The engine was selected to meet the required speed of the proposed CFRP SURC. The weight of the hull including the engine was then estimated to determine the loading conditions on the hull.

To estimate the engine output required to meet the desired maximum speed, the algorithms developed by Savitsky for planing and pre-planing speeds (Savitsky, 2012), which are mainly used for hull design, were applied using Maxsurf Resistance (Bentley, 2020). Fig. 6 shows the estimated change in the engine horsepower (hp) according to the change in speed. For an assumed engine efficiency of 65 %, and it was found that the proposed CFRP SURC requires about 400 hp at 40 knots and about 652 hp at 50 knots. After an investigation of relevant waterjet propulsion systems suitable for small craft, the Volvo Penta D6-370 (Volvo Penta, 2020) was selected as the main engine.

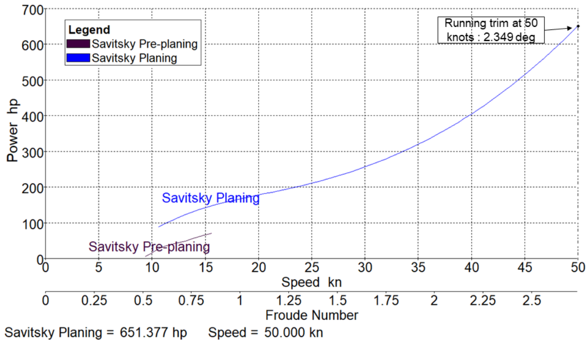


Fig. 6 Powering according to required speed

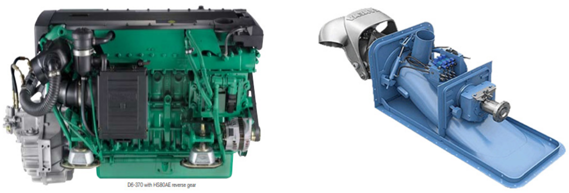


Fig. 7 Selected main engine (Volvo Penta, 2020) and waterjet (Kamewa, 2020)

Table 4 Loading conditions according to ISO 8666 & 12217

Items (ton)	Value	Note
m_{LCC} (+3 %)	4.154	Light weight condition
Pay load	0.750	8 crew members and personal effects
Liquid	0.500	Fuel oil
m_{MTL}	1.250	Maximum load (pay load + liquid load)
m_L	0.206	Min. crew (2) + safety equipment
m_{MOC}	4.361	m_{LCC}+ m_L
m_{LDC}	5.404	m_{LCC}+m_{MTL}

m_{MTL} : The mass of the Maximum total load
m_L : The mass of the load to be carried in the minimum operating condition
m_{MOC} : The mass of the craft on the minimum operating condition

For the waterjet unit, Volvo recommends using Kamewa's FF37 (Fig. 7). According to their online specifications, the D6-370 weight 580 kg per unit and the waterjet unit weighs 994 kg. To estimate the weight for each loading condition of the proposed CFRP SURC, the hull weight, excluding the weight of the engine m_{LCC}, was first estimated. The estimated loading conditions provided in Table 4 consist of the weight of the hull structure excluding liquids, the engine, fuel, and freshwater. Therefore, to determine m_{LCC}, the weight of two waterjets, 1,988 kg, should be included, and the weight of the crew, fuel, freshwater, and armament should be considered. The number of passengers was set to eight as per the preliminary requirements, and the fuel tank was assumed to weigh about 500 kg by referring to data from a similar ship. The fully loaded displacement calculated for the proposed SURC, m_{LDC}, was estimated to be 5.404 tons as shown in Table 4 using ISO 8666 and 12217 and the previously mentioned design tools.

3. Structural design of proposed CFRP SURC

In this chapter, the hull structure of the proposed CFRP SURC is designed with reference to the mechanical properties of the CFRP material suggested in the ISO standard, the design regulations of the CFRP hull structure covered by international classification societies, and the results of the previously reported CFRP laminate evaluations (Oh et al., 2019a). Then, the structural safety of the design is discussed according to the relevant regulations and experimental results.

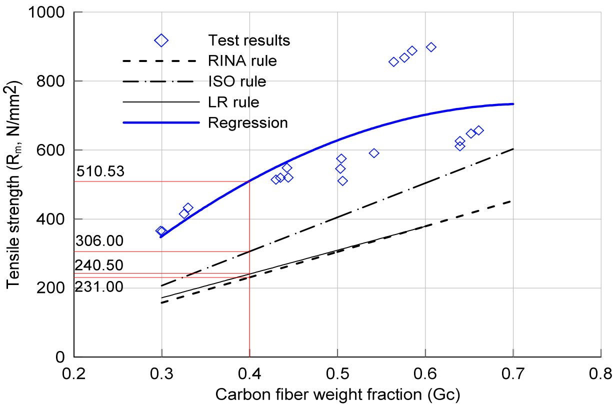
3.1 Material selection

Carbon-graphite fibers are recognized as laminate materials in ISO 12215, and are classified into several grades according to properties such as their tensile modulus. The Registro Italiano Navale (RINA) regulations, which conform well with ISO 12215, provide a design formula for the use of carbon-graphite fiber by dividing the carbon fiber textile they constitute into four grades. To be classified as a marine composite material, the composite must contain at least 30 % reinforcing fibers. Therefore, carbon fiber is considered effective only if is constitutes more than 30 % of the laminate structure. Though a method for the determination of the mechanical properties of the laminate according to the weight fraction of carbon fiber have been proposed, the most accurate way to determine the properties of CFRP laminates is to directly test the materials intended for application in the ship under development. Therefore, in this study the calculated mechanical properties are compared with the properties previously determined by material testing.

Fig. 8 depicts the tensile strength results calculated using the tensile strength estimation equations according to the weight fraction, Gc, of carbon fiber as suggested by the ISO standard, RINA, and Lloyd's Register (LR) specifications (RINA, 2019; LR, 2019). The strength was determined for a carbon fiber Gc from 30 % to 70 %. The calculated tensile strengths are compared in Fig. 9 with the previously reported CFRP test results (Oh et al., 2019a). The carbon fiber textile used for the CFRP tests was 400 g/m^2 and made of woven roving (WR) (Hyosung, 2017), which is an intermediate carbon

IM grade according to the RINA specifications. The CFRP laminates were fabricated to contain a carbon fiber Gc of 30 % to 65 %, and the ratio of the carbon textile plies to polyester resin was controlled (Fig. 9). Five types of CFRP laminates were fabricated in thicknesses ranging from 2.94 mm to 3.50 mm and the carbon textile was used in quantities of 3 to 10 plies. The results of the fabricated CFRP laminate material tests, conducted according to ASTM D3039 (ASTM, 2017a) and ASTM D790 (ASTM, 2017b), are shown by the blue diamond points in Fig. 8, and approximated by the regression indicated by the blue line.

It can be observed in Fig. 8 that the tensile strengths calculated according to RINA and LR are more conservative than those calculated using the ISO standard, and that the experimentally determined tensile strengths of the actual CFRP are higher than any calculated results.



Item	Equations
ISO rule	$R_m = 990Gc - 90$
RINA rule	$R_m = 740Gc - 65$
LR rule	$R_m = 690Gc - 35.3\ (0.3 \le Gc \le 0.6)$
Test regression	$R_m = -2159.09Gc^2 + 3117.76Gc - 391.12\ , R^2 = 0.60$

Fig. 8 Comparison of the strength determined according to design specification with the strength determined from experiment results according the weight fraction (Gc) of carbon fiber

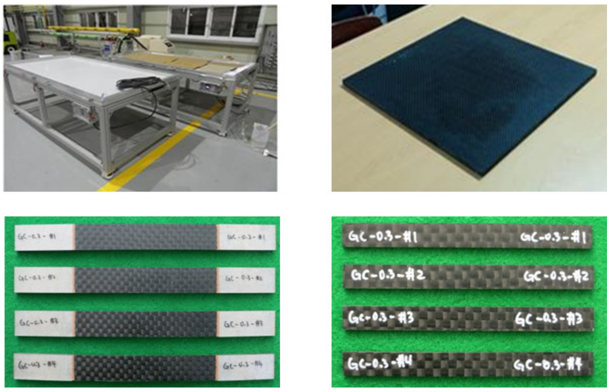


Fig. 9 CFRP laminate specimens for tensile and flexural testing (the case of 30 % carbon fiber woven roving) (Oh et al., 2019a)

The material used for the laminate structure of the proposed CFRP SURC was assumed to be the same material for which the experimental results were available, and the carbon fiber Gc used in the design of the laminate structure was selected to be 40 %. To completely design the CFRP structure, the mechanical properties of the selected material must be estimated. This estimation was accomplished using the following equation suggested in the RINA specifications.

$$\begin{aligned}&Tensile\ strength : R_m = 740Gc - 65 \\ &Compressive\ strength : R_{mc} = 460Gc - 40 \\ &Flexural\ strength : R_{mf} = 2.5R_m/(1 + R_m/R_{mc})\end{aligned} \tag{1}$$

where Gc is the Carbon fiber weight fraction.

Table 5 summarizes the calculation results for a 40 % carbon fiber Gc, which can be compared with the experimental results shown in Fig. 8. The experimental result provided a tensile strength 510.53 N/mm^2, which considerably exceeds the value estimated using the RINA specification. Therefore, no problem is expected in terms of the physical performance of this carbon fiber textile, though the strength of the structural design will be evaluated again based on the design results and experimental results in Section 3.2 to confirm. Table 6 summarizes the raw material information of the selected CFRP laminate required for the structural design.

Table 5 Mechanical properties of CFRP estimated using RINA specifications

Items (N/mm^2)	Value
Tensile strength (R_m)	231.00
Compressive strength (R_{mc})	144.00
Flexural strength (R_{mf})	221.76

Table 6 Raw material information for CFRP structure design

Items		Value
Reinforcement	Fiber type	Carbon fiber
	Fabric form	Woven roving
	Weight per unit area of fabric (g/m^2)	400
	Fiber density (g/cm^3)	1.8
Matrix	Resin type	Polyester
	Relative density	1.2
Core material	Type	PVC
	Density (kg/m^3)	100

3.2 Laminate design of CFRP structures

The structural layout, including hull division and stiffener arrangement, was performed using the previously developed hull form, and a watertight bulkhead was placed in consideration of the main engine location according to the RINA specifications. The detailed structural layout results are shown in Fig. 10. The overall structural design was performed in accordance with RINA specifications, and the detailed design process was conducted as described in Oh et al. (2014).

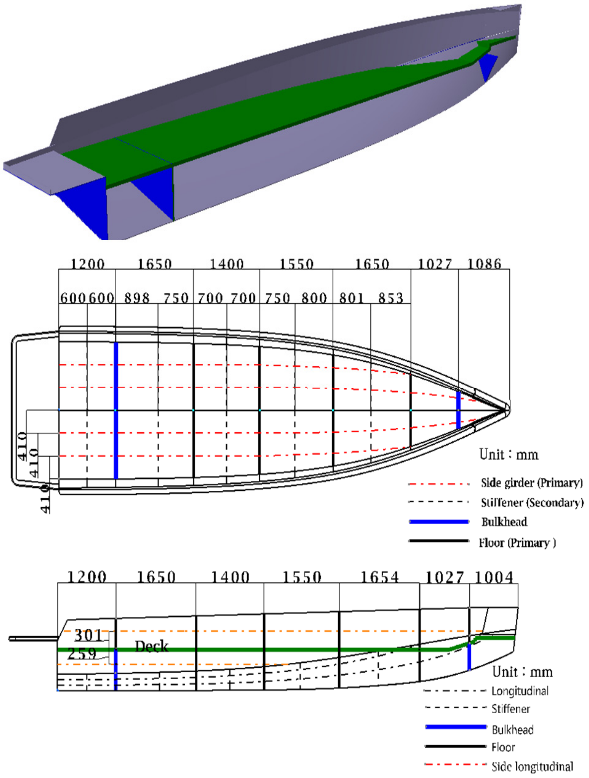


Fig. 10 Structural layout of the design ship

First, the CFRP structure design was performed mainly for the laminate of the bottom hull plate, where the maximum slamming load is expected. To estimate the design load acting on the hull, a maximum speed of 50 knots was applied, and the equations corresponding to a planing craft were used to determine as hydrostatic head and impact pressure acting on the hull according to:

$$P_1 = 0.24\sqrt{L_{WL}}\left(1-\frac{h_0}{2T}\right)+10(h_0+aL_{WL}) \qquad (2)$$

$$P_1 \geq 10D$$

$$P_2 = 15\frac{\Delta}{L_{WL}\times C_s}g(1+a_V)\times F_L\times F_1\times F_a \qquad (3)$$

where L_{WL} is the length of full load waterline, T is the full load draft, h_0 is the distance between pdr and full load waterline, a is the coefficient function as the longitudinal position of pdr, D is the depth, Δ is the full load displacement, F_L is the coefficient function as the longitudinal position of pdr on impact pressure, F_1 is the coefficient function as the shape of the hull, F_a is the coefficient function as the size of design area, a_V is the maximum design value of acceleration, C_s is the girth distance of the craft at $0.5L_{WL}$.

Fig. 11 depicts the longitudinal impact pressure determined using Equation (3) for all design areas below the waterline of the hull. The maximum design load was determined to be the result of slamming at the front of the midship and was calculated to be 74.5 kN/m^2.

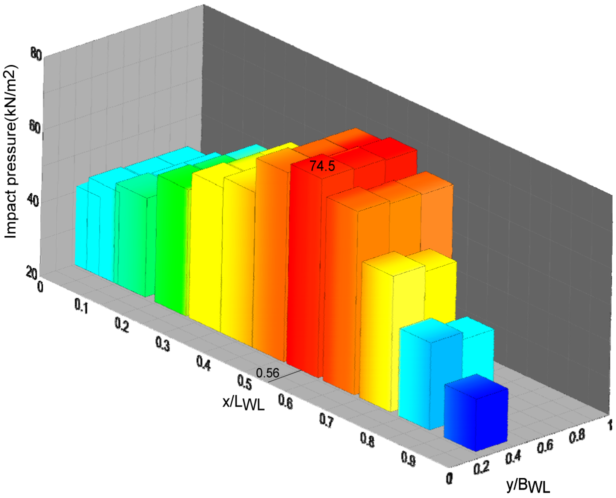


Fig. 11 Impact pressure acting on every design area of the bottom hull plate

The required laminate thickness for the bottom hull plate was then calculated using the calculated loads in Fig. 11 according to the RINA specifications (RINA, 2019) by

$$T_1 = K_1\times s\times K_a\times P^{0.5}\times\left(\frac{152}{R_{mf}}\right)^{0.5} \qquad (4)$$

$$T_2 = 16\times s\times D^{0.5}\times\left(\frac{152}{R_{mf}}\right)^{0.5} \qquad (5)$$

where K_1 is the safety coefficient by design pressure type, K_a is the coefficient of the ratio S/s of design area, s is the short dimension of design area, S is the long dimension of design area, P is the design pressure, R_{mf} is the flexural strength of the laminate.

The results are shown in Fig. 12, which indicates that a thickness of 10.40 mm or greater is required at 0.56 L_{WL}, where the maximum slamming force acts on the bottom plate of the hull. This required thickness was used to design the CFRP laminate for the entire hull.

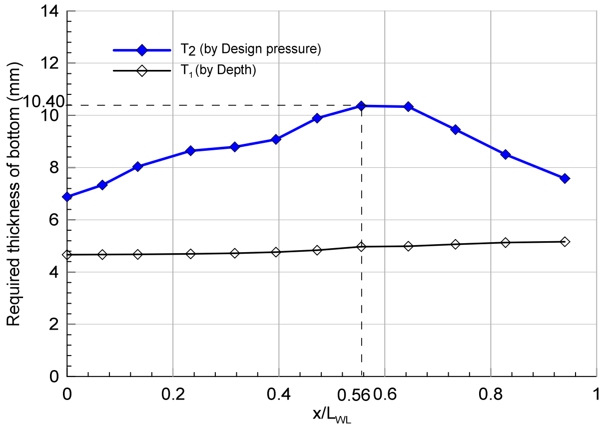


Fig. 12 Required thickness of design area according to longitudinal pressure on the bottom hull plate

A CFRP laminate was thus designed using the carbon WR textile selected in the previous section to meet the required bottom hull plate thickness. When using 40 % carbon fiber WR textile at a density of 400 g/m^2, the average thickness of a single ply can be calculated by

$$T_{single} = \frac{p}{2.16} \times \left(\frac{1.8}{Gc} - 0.6\right) \tag{6}$$

where T_{single} is the thickness of a single layer of the laminate, p is the weight per unit area of carbon fiber fabric.

indicating that a thickness of a single play is around 0.72 mm. In other words, to meet the required 10.40 mm thickness of the bottom hull plate, at least 15 plies of carbon WR textile are required, yielding a thickness of 10.80 mm, as calculated by

$$T_{mfrg} = \sum_{1}^{n} T_{single} \tag{7}$$

where T_{mfrg} is the thickness by manufacture design.

However, it was decided that 16 plies should be applied to provide a 10 % design margin for the required thickness, making the designed thickness of the CFRP laminate of the hull bottom plate 11.52 mm.

The same process applied to the CFRP laminate design of the bottom hull plate was applied to the design of other vessel structures such as the side plates, decks, and bulkheads. The design of stiffeners including a polyvinyl chloride (PVC) core material was also performed. The resulting designs of these CFRP structures are summarized in Table 7 and shown in Fig. 13. This design data was then used to re-estimate the light craft weight in detail.

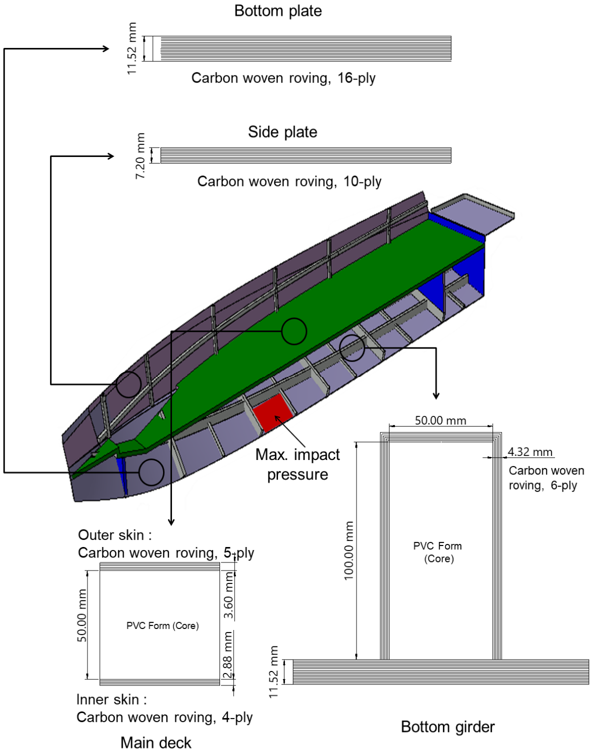


Fig. 13 Main shapes of the designed CFRP structures

Table 7 Designed CFRP structures in the design ship

Hull structure			Thickness (mm)	Carbon WR (Plies)
Keel			16.56	23
Bottom plate			11.52	16
Side plate			7.20	10
Sheer strake			9.36	13
Stiffener	Bottom girder	Core	50.00×100.00	-
		Web/Flange	4.32	6
	Bottom floor	Core	50.00×150.00	-
		Web/Flange	7.92	11
	Side longitudinal	Core	50.00×50.00	-
		Web/Flange	2.88	4
	Side frame	Core	50.00	-
		Web/Flange	2.88	4
Main deck (Sandwich)		Outer skin	3.60	5
		Inner skin	2.88	4
		Core height	50.00	-
Subdivision/ Collision bulkhead (Sandwich)		Outer skin	2.88	4
		Inner skin	2.88	4
		Core height	50.00	-

3.3 Longitudinal strength evaluation

Next, the structural design results were evaluated to determine longitudinal strength of the midship according to the RINA specifications (RINA, 2019) and were compared with the experimentally determined material properties of the CFRP laminate used for the hull.

The bending moment acting on the proposed CFRP SURC was calculated to be 131.85 kN·m by

$$\sigma_h \le f \times \sigma_i \tag{8}$$

where σ_h is the maximum bending stress, f is the safety coefficient, 0.33 for planing craft, σ_i is the less value of tensile and compressive strength.

The longitudinal strength was then evaluated in relation to the allowable stress of the CFRP according to the specifications and material test results, with the results shown in Table 8.

Table 8 Comparison of the longitudinal strength evaluation based on specifications and experiments

Items	Specification	Material test
Maximum bending stress (σ_h, N/mm^2)	17.58	17.58
Allowable stress ($f \times \sigma_i$, N/mm^2)	76.23	168.47
Safety margin ($\sigma_h / (f \times \sigma_i)$, %)	76.94	89.56

The results of the evaluation confirmed that both the hull slamming and longitudinal bending cases were within the strength requirements of the structure design, and that the thickness and section modulus of the CFRP were very conservative. In particular, the experimental results shown in Fig. 8 suggest that for a carbon fiber Gc of 40 %, the tensile strength was 510.53 N/mm^2, which is more than twice as large as the 231.00 N/mm^2 value estimated using the specification, so that the allowable stress could considered quite larger than the design value used. This would lead to an increase of 12.62 % in the safety margin.

The potentially higher allowable CFRP SURC could be minimized by reducing the total amount of carbon fiber required through the careful arrangement of structures and re-design of the CFRP laminate based on experimental results rather than specification-calculated results. This also suggests that the specific strength can be maximized by providing the optimum amount of carbon fiber. The process of maximizing the specific strength of the CFRP based on the experimental results is described in detail Section 5.2.

4. DMU of proposed CFRP SURC

The general characteristics of an SURC and the specifics of its intended operating area presented in Section 2 are reflected externally and kinematically. In this section, a DMU of the proposed CFRP SURC is presented that was built by applying these geometric features based on the developed hull form and structure.

First, the engine was placed and assembled inside the engine room, and because a drawing of the selected waterjet model could not be obtained, it was replaced with a similar model and assembled into the hull. The cabin size was minimized considering vessel stability due to the reduced weight of the hull, and the helm station was designed to secure pilot vision in an open form. Standing seats were installed to ensure stable seating and rapid movement of passengers even at high speeds. Walls made of armored glass were placed around the helm station and passenger seats, and weapon spaces were secured for small arms such as Gatling guns at the front and the rear. A ramp structure was introduced to the bow section for quick berthing and crew movement. Fig. 14 shows the completed SURC DMU model.

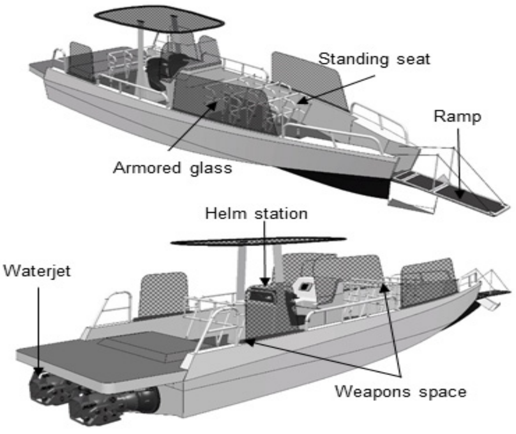


Fig. 14 3D DMU of the proposed CFRP SURC

The relatively shallow draft of the proposed CFRP high-speed SURC and the large windage area of the hull side were confirmed, but these shape characteristics need to be corrected through a more thorough stability check in future research.

5. Discussion of CFRP application in an SURC

5.1 Lightweight effect compared to Aluminum hull

The weight of the proposed CFRP SURC under the light condition excluding the engine was determined to be 2.103 tons based on Table 2, but this number is based on the statistics of similar craft. The actual weight of the vessel structure itself can be determined from the CFRP laminate design results for each structure. Table 9 shows that the calculated weight of the proposed CFRP SURC structure estimated from the 3D CAD model of the structure design is 1.239 tons. Because the total weight of the previously selected waterjet unit is 1.988 tons, the m_{LCC} is 3.227 tons. This constitutes a difference of about 1 ton from the estimated value shown in Table 4, which can be considered to account for the weight of armaments and electronic communication equipment.

Table 9 Structure weight calculation from the 3D CAD model according to hull structure component

Hull Structures		Weight (kg)
Keel		121.10
Bottom plate		332.67
Side plate		244.87
Sheer strake		54.35
Stiffener	Bottom	131.29
	Side	21.49
Sandwich	Main deck	175.43
	Bulkhead	14.05
Core material		144.74
Total		1,239.99

The displacement tendencies of an existing aluminum SURC and several CFRP high-speed craft are compared with those of the proposed CFRP SURC in Fig. 15, in which the black line shows the displacement tendency of an aluminum SURC investigated by Lee et al. (2011), and the blue line shows displacement tendencies of the CFRP-I, -II, -III, -IV, and -V craft, defined in Table 1. The proposed CFRP SURC, indicated by the blue square, was found to be about 41.49 % lighter than the aluminum SURC.

According to Stenius et al. (2011), 11.7-ton high-speed ships made of aluminum have been reported to weigh about 50 % less if redesigned using a CFRP sandwich structure. The design results of the proposed CFRP SURC clearly show a similar weight reduction tendency. However, the weight of the proposed CFRP SURC was found to be about 36.64 % heavier than similar CFRP craft, but this discrepancy can be attributed to the additional weight of the propeller and armaments. Indeed, more special GFRP and aluminum ships have been constructed recently using CFRP instead because of its light weight; according to Oh et al. (2018), redesigning a 12-ton GFRP power yacht with a CFRP single-skin plate can reduced the weight of the vessel by about 45 %.

This lightweight effect can increase engine efficiency and extend the operational range of the vessel. Using the fuel consumption chart in the engine specification catalog provided by Volvo, the changes in fuel consumption and operating range were determined according to the expected weight reduction. The fuel consumption of a 9.236-ton aluminum SURC and the 5.404-ton proposed CFRP SURC are compared at 40 knots in Fig. 15, in which it can be

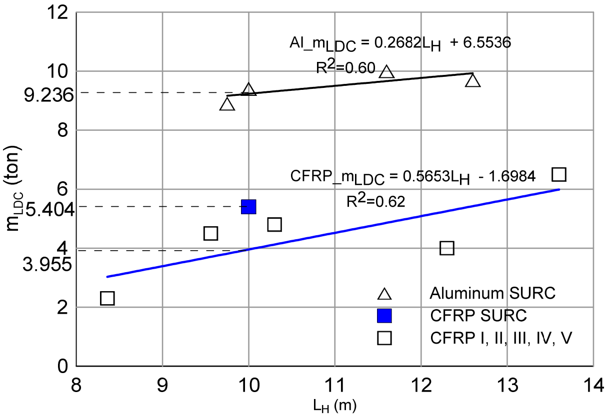


Fig. 15 Comparison on the lightweight effect of the proposed CFRP SURC with an actual aluminum SURC and several actual CFRP craft

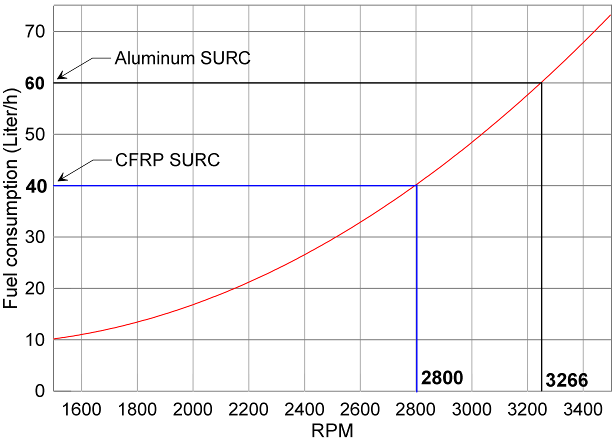


Fig. 16 Comparison on fuel consumption of the proposed CFRP SURC with an aluminum SURC according to change in RPM (at 40 knots)

observed that the proposed CFRP SURC saves about 33 % fuel consumption per hour. These savings are equivalent to being able to sail an additional 20 NM for every hour the engine is run. Among these process, Fig. 16 shows the estimation results of fuel consumption per an hour of the CFRP SURC and the aluminum SURC from one engine.

5.2 CFRP design considering economic feasibility

The high specific strength of CFRP not only reduces the weight of the structure it constitutes but also provides excellent performance. Based on the longitudinal strength evaluation results in Table 8, it can be confirmed that by using the calculation method provided in the RINA specifications for the CFRP laminate strength instead of the experimental results, the structural design was 12 % more conservative. Therefore, it should be possible to design the proposed CFRP SURC more economically by using the experimentally determined strength of the CFRP.

The extremely high material cost of CFRP can be a fatal drawback when considering its application. Therefore, in consideration of economic feasibility, the specific strength of vessel components should be maximized through the optimal design of the CFRP laminate. The strength of CFRP with a carbon fiber Gc of 40 % shown by the experimental results in Fig. 8 is more than twice the strength of an equivalent thickness of marine aluminum typically used for building high-speed craft (Kang, 2005; Oh et al., 2019b). Therefore, it should be feasible to reduce the amount of carbon fiber to some extent. For example, for the strength of CFRP with a carbon fiber Gc of 40 %, according to the specifications and based on the results shown in Fig. 8, the same performance can be achieved with only about 24 % of the carbon fiber material. Even if the thickness of the CFRP laminate is maintained at 11.52 mm for structural simplicity, the number of WR textile plies can be reduced from 16 to 9 in most places. Because marine composite materials are required to be more than 30 % reinforcing fibers, the number of plies can be reduced by 5 to 11 even when recalculated for the lowest carbon fiber Gc of 30 %. Table 10 summarizes the process of calculating the change in the number of required carbon WR textile plies according to carbon fiber Gc.

If this varying carbon fiber content design concept is applied, the optimum CFRP laminate design can provide specific strength characteristics by increasing the weight of carbon fiber where necessary while using less carbon fiber elsewhere, improving the economics of CFRP as a SURC hull material.

Table 10 Reduction of carbon fiber WR textile considering experimentally determined mechanical properties

Item	Rule	Material Test I	Material Test II
Gc	40 %	24 %	30 %
Required thickness (mm)	10.40	10.40	10.40
T_{single} (mm)	0.72	1.28	1.00
Carbon WR cloth (Ply)	16	9	11
T_{mfrg} (mm)	11.52	11.52	11.00
Weight of carbon fiber (kg/m^2)	6.40	3.60	4.40

6. Conclusion

In this study, an SURC, which is typically made of aluminum, was designed using CFRP to conduct a feasibility study. Based on international standards, several CFRP hull structures were developed and verified through a comparative analysis using previously reported material test results. Furthermore, by constructing a DMU model, it was possible to examine the basic shape and function of the proposed CFRP SURC.

It was confirmed that CFRP can meet all of the basic SURC requirements, such as low draft and fast maneuverability, when used as a hull material. It was also confirmed that a CFRP hull can be constructed about 40 % lighter than an equivalent aluminum hull. Moreover, the proposed CFRP hull exhibited much better specific strength properties than an aluminum hull under similar conditions. These design results confirmed that the proposed CFRP SURC would be able to perform operations faster even at lower drafts, and with a higher engine efficiency and a larger operating radius. Therefore, it was confirmed that CFRP is well-suited to the main objectives of an SURC. Through analysis, it was confirmed that when the high specific strength and easy fiber content adjustment of CFRP is considered to optimize the hull design, the disadvantages of the high raw material cost of carbon fiber can be overcome to some extent.

Because this study was conducted based on international standards, if the SURC is considered to be a special purpose vessel, it may be possible to further improve the performance of the proposed CFRP SURC considering more specific purposes. Accordingly, further model tests, more detailed structure designs, and additional material tests remain to be conducted in order to improve the proposed design. It is expected that the results of this study will be used as foundational data to inform the design of CFRP high-speed craft, for which there are currently few basic studies.

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