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Research paper

Environmental implications of a sandwich structure of a glass fiber-reinforced polymer ship

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ABSTRACT

This study presents the findings related to the selection of composite structures for materials with respect to the effectiveness of their lightweight design and environmental impact during the raw material manufacturing phases. The primary raw materials considered were glass fiber, PVC for the core, and polyester resin. In addition, using the same design conditions, such as bottom load, impregnation rate, and production method, a reverse engineering approach was applied to transform the sandwich structure into a single laminate structure, allowing for a comparative quantitative analysis of the reduction in lightweight effectiveness. The results revealed that the sandwich structure was approximately 42.44% lighter than that of the reverse-engineered single-skin laminate structure. A life cycle evaluation was also conducted, and the raw materials required for hull construction were analyzed with SimaPro 9.0 as the LCA tool software, Ecoinvent 3 for inventory analysis, and the ReCiPe 2016 method for environmental impact analysis. PVC foam and polyester resin were identified as highly hazardous for both human and environmental health, whereas fiberglass exhibited the lowest emissions among the materials considered. Furthermore, the sandwich structure offered greater environmental advantages across all damage endpoints than the single-skin laminates. This finding highlights the potential of sandwich structures as a more sustainable option. In practical terms, enhancing the bending strength of the core material in sandwich structures can reduce the thickness of the outer and inner skin members, thereby reducing the weight of ships and significantly reducing potential health risks to human worker health, harm to the ecosystem, and resource demands.

1. Introduction

The global economic boom and rapid expansion of technology have resulted in enormous amounts of resources being consumed by various industries yearly. Recently, fuel prices have been persistently high, resulting in an increase in prices of raw materials, such as those used in transportation and shipping industry products. Therefore, some manufacturers are seeking substitute materials to save costs and conserve energy. Moreover, to reduce environmental deterioration, more eco-friendly materials that have a lesser environmental impact are being increasingly applied in many industrial fields (Djurberg, 2012).

Fiber-reinforced polymers (FRP) have been widely used for decades in various fields, such as aviation, aerospace, automobiles, and ships, owing to their excellent specific strength, durability, workability, and corrosion resistance (Summerscales et al., 2016). However, these composite materials suffer from challenges, including environmental issues and difficulties in recycling that occur during manufacturing and disposal processes (Pickering, 2006). Moreover, there is still limited availability of sustainable end-of-life waste management technology due to the limited amount of known applications and lack of innovation (Chatziparaskeva et al., 2022). Additionally, long-term disposal and scrapping of composite materials through incineration and landfills, which are widely used, can have severe environmental impacts such as increased ecotoxicity and carcinogens (Hou, 2011). As the interest in environmental protection is increasing worldwide, various methods have been introduced and gradually used, such as mechanical processes,

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pyrolysis, thermal processes, and solvolysis (Kawajiri and Kobayashi, 2022). Other studies have also been conducted to emphasize reusability using biotechnological methods, such as high-power ultrasound, in combination with surface activation methods to accelerate the replacement of landfilling options (Sourkouni et al., 2021). However, these methods are relatively expensive compared to the methods of disposing of composite materials, such as landfills or incineration (Krauklis et al., 2021); therefore, the method of disposal rather than recycling is still widely used. Even composite ships are often left on shores without being disposed of after their lifespan. Consequently, studies on the design of lightweight structures (Han et al., 2020; Jang et al., 2019; Oh et al., 2018, 2020; Stenius et al., 2011) and change and improvement of the manufacturing method (Bianchi et al., 2021) to reduce environmental pollution caused by composite materials and the amount of waste in the disposal stage (Bianchi et al., 2021) have also been actively pursued.

In the marine field, composite materials are widely used in manufacturing hull structures of small ships, such as fishing boats and leisure ships (Selvaraju and Ilaiyavel, 2011). Moreover, composite materials are used to develop the primary hull of a significant proportion of small (Rubino et al., 2020) and medium-sized ships (Mouritz et al., 2001), as shown in Fig. 1 (Oh et al., 2022). Typically, primary structures such as the hull plate are manufactured in the form of a single skin lamination structure (as shown in Fig. 2(a)), and fabricated using fiberglass and resin as raw materials based on a mold (Fig. 2(b)) (Jang et al., 2023).

A lightweight hull structure design algorithm was developed specifically for single skin lamination to improve the eco-friendly performance and efficiency of composite fishing boats and leisure ships (Han et al., 2021), which confirmed that the weight could be reduced. Thus, it can be concluded that the eco-friendly performance is improved when the ship hull has a significant lightweight effect (Oh et al., 2019). As a result, the lightweight effect of the ship hull can positively impact energy efficiency and eco-friendly performance, thus increasing the ship service speed, reducing fuel consumption, and reducing air pollutants during the operation phases (Umair, 2006).

A significant weight reduction effect is obtained (Burman et al., 2016; Stenius et al., 2011) when a sandwich structure comprising a light core material such as polyvinyl chloride (PVC) foam applied to the composite material is used for the hull. Consequently, the sandwich structure is widely applied as hull decoration and structure material for parts such as hull shell plate, bulkhead, and deck. Significant weight reduction correlates with the impact on the operation phase, which is very high on abiotic depletion because the usage of fuel results in resource depletion. Therefore, the significant weight reduction effect contributes to fuel efficiency and reduces resource depletion (Cucinotta et al., 2017).

However, in addition to reinforcement (fiberglass) and resin, sandwich panels include a third material, such as PVC foam as shown in Fig. 3. The PVC foam complies with RINA rule (Table 1) and is widely used in hull sandwich structures. However, it can emit toxic chemicals during production, usage, and disposal, adversely affecting human health (Sapuan et al., 2022; Rodrigues et al., 2019) and water quality, in addition to causing global warming and soil acidification (Comaniţă et al., 2015).

Several studies have explored the environmental impact of various materials and compared composite materials with other material options, such as steel, aluminum, and wood, as primary hull materials (Burman et al., 2016; Umair, 2006; Hou, 2011; Pommier et al., 2016). In these studies, researchers aimed to showcase the impact of various hull materials, including composite materials, on the environment. Life cycle analysis in these studies showed that using composite material as the primary hull material leads to a considerable reduction in emissions compared to other materials. Additionally, research has been conducted on the environmental impact of two different manufacturing methods for composite material yachts (Cucinotta et al., 2017). The primary focus of this study was to identify the most environmentally friendly manufacturing methods. However, there is a notable gap in the literature concerning a comprehensive assessment of the environmental impact associated with the selection of a composite-type structure.

Understanding the correlation between structure type, lightweight effect, and eco-friendly performance in terms of environmental impact is necessary. Thus, this study aims to conduct a comparative analysis and investigate the correlation between various sandwich structures, which consist of PVC foam as core material and single skin laminate constituting different proportions of fiber glass and polyester resin. The study examined the impact of the environment during the production phases using life cycle assessment (LCA) in accordance with IMO regulations. Additionally, the study aims to assess the health risks for workers, damage to the ecosystem, and impacts on resource availability. The objective is to gain a better understanding of the implications associated with the selection of a particular structure type.

2. Research method

This study redesigned a 10-m-class leisure vessel with a sandwich composite material into one with a single-skin laminate composite material under the same design conditions (Fig. 4). The initial design case study ship incorporated fiberglass, resin, and PVC as the core materials in the sandwich structures. Under the same designed pressure load and mechanical properties, the case study ship is designed to single skin laminate structure with the absence of PVC material. Both structures underwent a lightweight effect analysis to better understand the correlation between structure types and the lightweight effect.

The investigated ship was used for a comparative analysis between two types of structures during the manufacturing phase, comparing

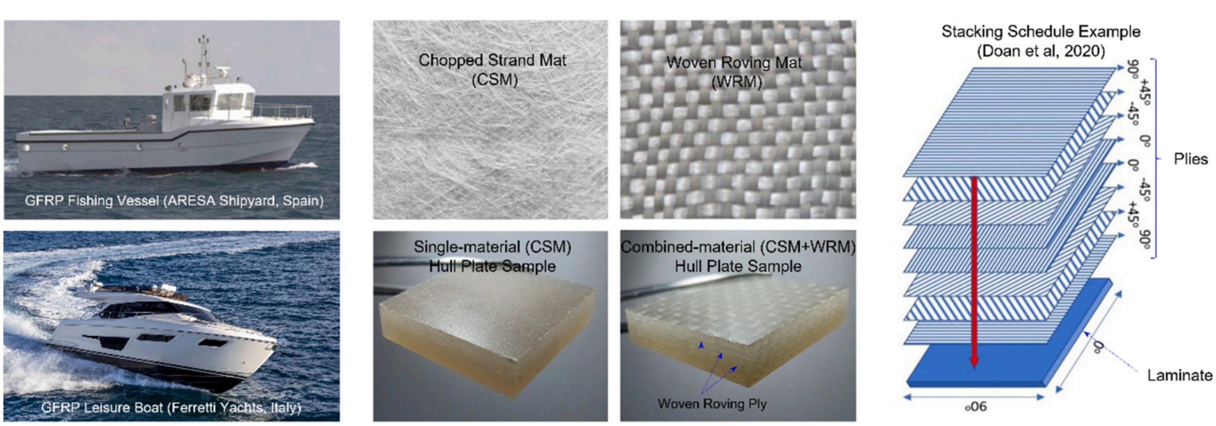

Fig. 1. Photographs of GFRP composite vessels, mats, laminates, and illustration of fabrication characteristics (Oh et al., 2022).

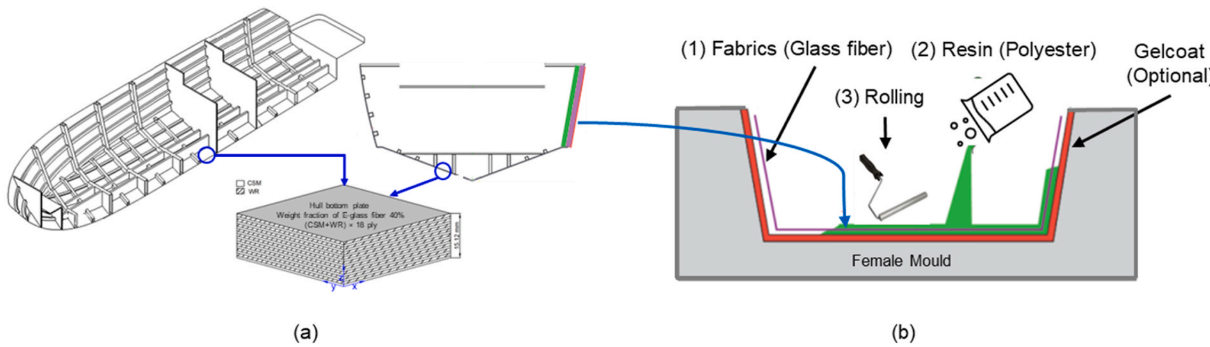

Fig. 2. Illustration of hull plate lamination and its manufacturing method. (a) Hull laminate design example; (b) hand lay-up process of fiber reinforced ship (Jang et al., 2023).

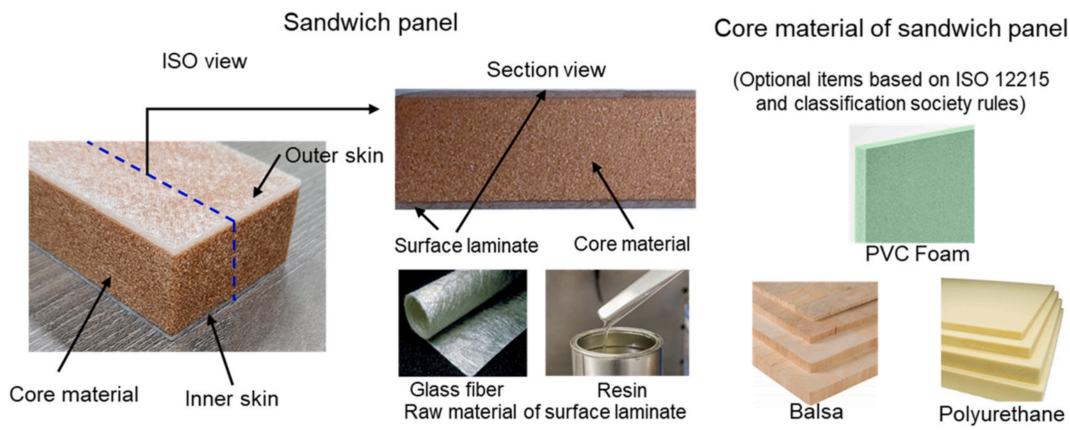

Fig. 3. Illustration of sandwich structure and its composition of raw material.

Table 1
Core materials are to be type-approved by RINA (RINA, 2022).

Material	Density (kg/m^3)	Minimum shear strength (N/mm^2)
Balsa End-Grain	104	1,6
	144	2,5
PVC, Crosslinked	80	0,9
	100	1,4
PVC, Linear	80–96	1,2
Polyurethane	90	0,5

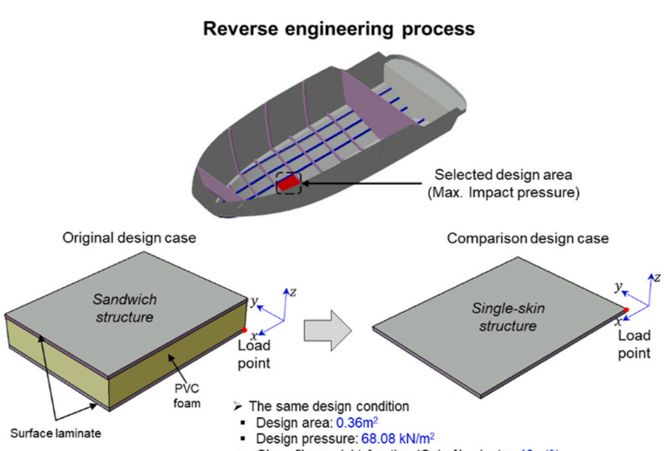

Fig. 4. Reverse engineering method involves the original sandwich structure to a comparison design case of single skin laminate.

sandwich composite structures and reverse engineering of a single-skin laminate using the LCA method. Sustainable design trends have grown rapidly as environmental pollution issues have attracted significant attention. Moreover, in the shipping industry, LCA has been extensively used to analyze environmental impacts (Gualeni and Maggioncalda, 2018; Islam et al., 2016; Popa et al., 2014; Jang et al., 2021). The concept of LCA is standardized under the ISO framework and has gained acceptance in environmental assessments. Therefore, in this study, LCA was applied to investigate and compare the environmental impacts of two different types of structures during the production phase using SimaPro 9 software with Ecoinvent 3 for inventory analysis and ReCiPe 2016 method for impact assessment. The analysis is conducted on a midpoint and endpoint index to compare types of structures that provide more sustainable options which are beneficial to human health, ecosystem and resource availability.

3. Target ship and materials

The ship investigated in this case study is a 10-m-class leisure vessel with the principal dimensions listed Table 2. In terms of operating conditions, the ship has a displacement of 7.68 tons with an operating speed of 25 knots. The ship was designed with the Registro Italiano Navale (RINA) rule under the rules for the classification of pleasure yachts, defining the standard for small ship structures, one of which employs a composite material (RINA, 2022). This designed ship structure is a sandwich composite panel consisting of the core material with crosslinked PVC foam developed by Dongsung chemical and outer/inner skin with chopped strand mat (CSM) and polyester resin having a glass content of 0.4. Crosslinked PVC foam contained 46 wt% methylene diphenyl diisocyanate (MDI) and had a density of 100 kg/m^3. Glass fiber CSM and polyester resin were used for the outer/inner skin, as

Table 2
Principal dimensions of target ship.

Principal dimensions		
Item	Value	Unit
L_{OA}	10.75	m
L	8.67	m
B_{wl}	3.77	m
D	1.60	m
Principal dimensions		
Item	Value	Unit
T	0.60	m
Δ	7.68	Ton
V	25.00	Knot
C_B	0.45	

summarized in Table 3. The ship was designed as a longitudinal type and two bulkheads. Mechanical properties are essential for designing variables when determining the number of laminate plies. In this study, the glass content ratio of the glass fiber was designed to be 40% for the outer and inner laminates of the sandwich laminate hull.

The design area with a design load of 68.08 kN/m^2 was estimated to be the largest on the bottom plate, which was selected as the study target for reverse engineering (Fig. 5). Under the same conditions as those for the design area, the specifications of the bottom sandwich structure were reverse-engineered to form a single-skin laminate structure. In the bottom sandwich panel design, the ship was designed with PVC foam with 25 mm as the core, four plies of glass fiber-reinforced plastic with 3 mm thickness as the outer surface skin, and three plies of glass fiber-reinforced plastic with 2.25 mm thickness as the inner surface skin.

4. Comparison of the weight between sandwich structure and single skin material

4.1. Reverse design process

Under the process design of a single-skin laminate structure, the required minimum thickness can be calculated using the same designed load (68.08 kN/m^2) as the largest pressure, spacing between stiffener and mechanical properties coefficient as the input. The mechanical properties coefficient, which considers the ultimate flexural strength, serves as the input for thickness calculation. With this information, the required thickness of the bottom plating (t_1 and t_2) with the greatest values required by rules can be calculated considering the spacing of ordinary longitudinal, coefficient designed, and ultimate flexural strength of the material described in (1) and (2). The ultimate flexural strength (R_{mf}) was calculated considering the glass content reinforcement in the laminate, as described in (3).

Table 3
Information on raw material.

Material	Item	Value	Unit
Fiber	Type	E-glass CSM	
	Unit weight	450	g/m^2
	Density	2560	kg/m^3
	Ultimate tensile strength	123.48	N/mm^2
	Ultimate compressive strength	132	N/mm^2
	Tensile modulus of elasticity	10,050	N/mm^2
	Shear modulus of elasticity	2920	N/mm^2
Resin	Type	Polyester	
	Density	1200	kg/m^3
PVC	Type	Crosslinked	
	Density	100	kg/m^3
	MDI	46	wt%
	Compression strength	2.10	Mpa
	Shear strength	0.92	Mpa
	Uniformity	6	%

$$t_1 = k_1 \times k_a \times s \times \left(\frac{152}{R_{mf}}\right)^{0.5} \times P^{0.5}, \quad (1)$$

$$t_2 = 16 \times s \times \left(\frac{152}{R_{mf}}\right)^{0.5} \times D^{0.5}, \quad (2)$$

$$R_{mf} = 502\, G_C{}^2 + 107, \quad (3)$$

where k_1 is the coefficient of the pressure type, k_a is the coefficient as a function of the ratio S/s, s is spacing of ordinary frames in m, R_{mf} is ultimate flexural strength in N/mm^2, P is scantling pressure in kN/mm^2, D is depth in m, and Gc is glass content of the fiber.

Accordingly, the thickness of a single ply of fiber laminate can be estimated by considering the density, glass content and weight per area of the fabric described in (4). In this study, the glass fiber density is 2.56 g/cm^3, and the polyester resin density is 1.2 g/cm^3. It is also possible to estimate the ply number considering the required thickness of plating by factoring to a design margin of 10% and single ply thickness described in (5). In a result, manufacturing thickness can be calculated considering the single ply thickness factoring with the number of ply needed described in (6). The manufacturing thickness should be larger than the required thickness.

$$t_{single\ ply} = \frac{p}{\rho_{fiber} * \rho_{resin}} \times \left(\frac{\rho_{fiber}}{G_C} - (\rho_{fiber} - \rho_{resin})\right), \quad (4)$$

$$n = \frac{t_{req} * (1 + 10\%)}{t_{single\ ply}}, \quad (5)$$

$$t_{mfrg} = \sum_{1}^{i} t_{single\ ply_i} \ , \quad (6)$$

where p is the weight per area of fabric in g/cm^3, t_{req} is the required thickness of the plating in mm and Gc is the glass content of the fiber.

4.2. Comparison analysis of the lightweight effect of sandwich structure compared to single skin laminate

Based on the single-skin laminate design, the manufacturing thickness of the single-skin laminate was determined to be 12 mm with a margin of 10%, and the laminate schedule was 16 plies of CSM (Fig. 6). The sandwich panel consisted of seven plies of CSM laminated on the PVC foam as the core, with a thickness of 30.25 mm. Hence, we concluded that the CSM fabric in a single-skin laminate was increased by nine plies compared with the sandwich panel structure. In addition, by analyzing the change in the raw materials according to the changes in the composite hull structure type, it can be concluded that the sandwich structure has a greater weight reduction effect than the single-skin laminate structure. It has been confirmed that the selected design area has an area of 0.36 m^2 based on the 3D model CAD. Changes in the raw material of the sandwich structure and reverse-engineered single-laminate skin were identified based on the design results (Table 4).

The total weight of the sandwich structure was 3.73 kg, and the reversed engineer single-skin laminated was 6.48 kg. This shows that the amount of raw material required in the single-skin laminate is more than twice that of the sandwich panel on glass fiber and resin. It was confirmed that the sandwich structure was approximately 42.44% lighter than that of reverse engineering with a single-skin laminate structure.

5. Life cycle assessment methodology (LCA)

The methodology employed for the environment impact assessment in this study adhered to ISO standards 14,040-14044 (ISO, 2006a; 2006b). It consists of four steps: goal and scope definition, inventory

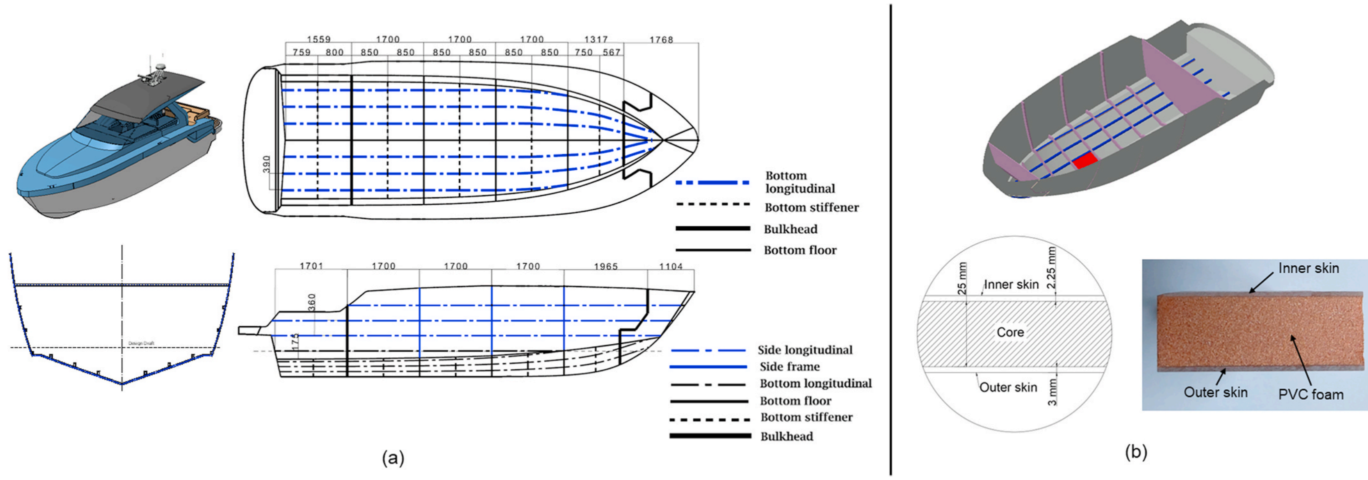

Fig. 5. (a) Target ship structural arrangement; (b) Specification of sandwich structure target ship.

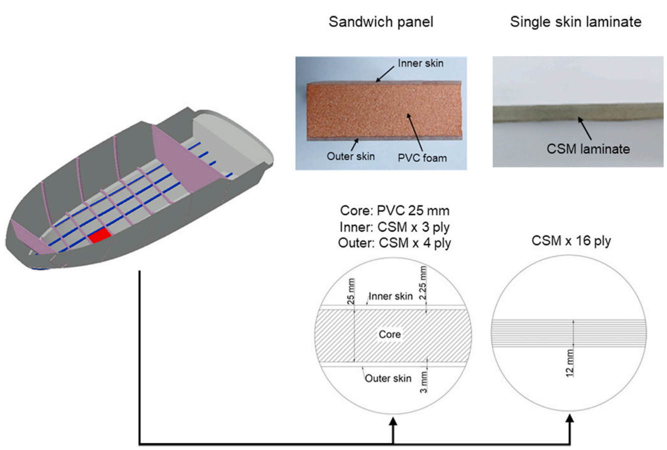

Fig. 6. Comparison of structure design results (sandwich panel vs. single skin laminate).

Table 4
Weight comparison of each structure.

Item	Sandwich structure (kg)	Single-skin laminate (kg)
Glass fiber	1.13	2.59
Resin	1.70	3.89
PVC core	0.90	–
Total	3.73	6.48

analysis, impact assessment, and interpretation (Rebitzer et al., 2004). This study applied LCA to compare the environmental assessments of the ship under investigation, considering both a sandwich structure and reverse-engineered single-laminate structures under the same design conditions associated with the IMO regulation. Additionally, the study was also conducted to evaluate the health risks to workers, damage to ecosystems, and resource availability, as shown in Fig. 7.

5.1. Goal and scope definition

In this study, the goal of LCA was a holistic assessment of the environment impacts of two types of FRP structures under the same design condition. Environmental impact analyses were focused solely on the impact of the raw materials on manufacturing phases. On the manufacturing phases, working environment is not considered in this analysis. The operational and end-of-life phases were not included in this study. To compare different types of composite structures, this study used a functional unit of a plate with a design area of 0.36 m^2 under the largest load on the bottom plate. SimaPro 9 software, a well-known tool, was used for analyzing the environmental impacts applied in this study. The framework used in this study is shown in Fig. 8.

5.2. Life cycle inventory (LCI)

The LCI considers the inputs and outputs of environmental loads in the life cycle study process. In this step, the inputs and emissions of the environmental load settings were quantitatively estimated and evaluated. Two types of structures, sandwich structure and single-skin laminate, were analyzed under the same design conditions. Usually, these two structures consist of fibrous reinforcement (fiberglass) and resin, whereas the sandwich structures comprise additional PVC foam as the core. Fiberglass and resin were combined mechanically and chemically to form a rigid laminate. The detailed proportions of both structures are summarized in Table 5. At this stage, the Ecoinvent 3 library, one of the most comprehensive databases, was used. The inventory consists of all database modelling of the product which aims to analyze the environmental impact flow including the raw material to the emission to air, water and soil.

5.3. Life cycle impact assessment (LCIA)

The LCIA was performed using Simapro 9. Translating environmental loads into impact categories is crucial for understanding a study's objective. Therefore, this study considers ReCiPe 2016 as an assessment methodology widely used to evaluate the environmental impacts of the two types of structures investigated.

The ReCiPe 2016 method is one of the most comprehensive methods that translate life-cycle inventories to environmental load on impact scores with midpoint and endpoint levels. This method considers 18 impact midpoint categories on specific environmental problems that provide characterization factors on damage pathways that lead to three damage endpoint categories: damage to human health, damage to ecosystems, and damage to resource availability (Huijbregts et al., 2017).

The IMO regulation was used in the environmental impact assessment as a basis for this study. The IMO regulations for environmental impact assessment consist of five types: global warming potential (GWP), ozone depletion potential (ODP), acidification potential, ozone formation potential (OFP), terrestrial ecosystems and ozone formation potential (OFP), and human health. The input derived in the inventory analysis is the weight of various environmentally loaded compounds during the production of raw materials, such as glass fiber, resin, and

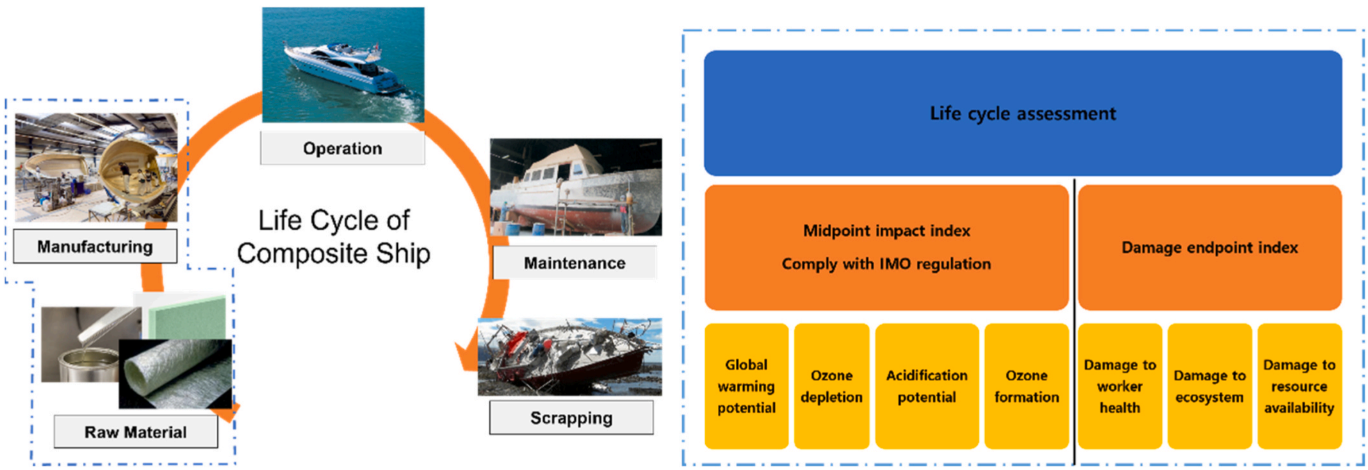

Fig. 7. LCA process of the study which considers in manufacturing phase and the assessment index.

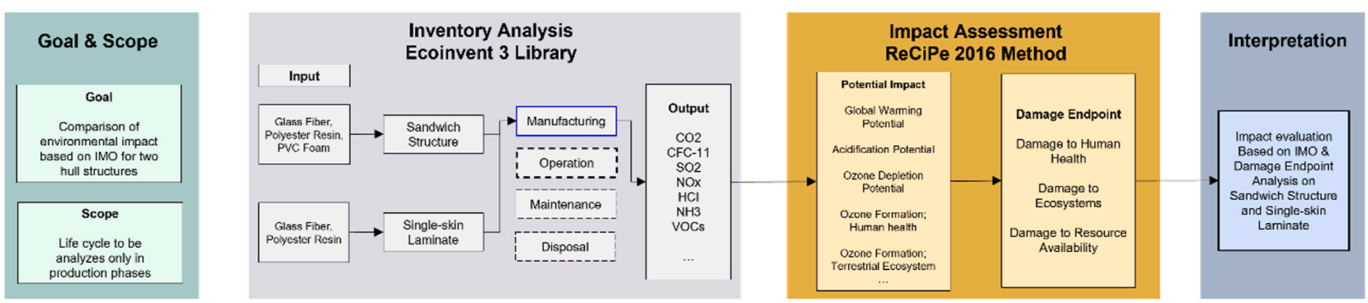

Fig. 8. System boundary framework of LCA apply in this study which align with the ISO framework.

Table 5
Raw material weight input.

Raw material					
Item	Density (kg/m^3)	Weight of 1 m^2		Weight Input of 0.36 m^2	
		Sandwich (kg)	Single skin (kg)	Sandwich (kg)	Single skin (kg)
Glass fiber	2560	3.14	7.19	1.13	2.59
Resin	1200	4.72	10.81	1.70	3.89
PVC foam	100	2.5	–	0.90	–
Total	–	–	–	3.73	6.48

PVC foam, which are essential for producing the two structural types. Characterization and classification method is applied to the interpretation on each impact category which are aggregated and normalize to 100% of results.

6. Results of impact assessment

This study considered the analysis only of the impact of raw materials during the manufacturing phase, and the impact values were derived using SimaPro software. The impact analysis results are presented in the following subsection according to the goals and scope of the study.

6.1. Assessing environmental impact index during production phases with regard to IMO regulation

This study applied IMO regulations to conduct a comparative analysis of five midpoint indices, evaluating and investigating the impact of the composition of the structure's raw materials. According to Fig. 9, considering 1 kg of raw material for analyzing environmental impacts, polyester resin contributes 100% of the environmental impact in nearly all categories except terrestrial acidification. In most cases, polyester resin contributes significantly to the environmental impact compared to other raw materials. Additionally, PVC foam contributes the most to the terrestrial acidification index categories. Interestingly, regarding the ozone depletion category index, glass fiber contributes less than 10% to the depletion of the ozone layer. Furthermore, as a raw material, fiberglass contributed the least to the environment among the other raw materials in all index categories.

6.2. Comparison analysis of damages to human worker health during production phases

This study considers damages to human worker health using four indices: increase in respiratory disease, various types of cancer, other diseases, and malnutrition. When considering 1 kg of each raw material, as shown in Fig. 10, PVC foam emerged as the most toxic to worker health in nearly all aspects, except the malnutrition index. Polyester resin exhibited the highest toxicity in the malnutrition index and closely followed PVC foam in other indices. In terms of toxicity to worker health across all indices, emissions from glass fiber are significantly lower than those from other materials, indicating a substantial reduction. Consequently, glass fiber contributed the least damage to worker health during the production phase.

6.3. Comparison analysis of damages to ecosystem and resource availability during production phases

In this section, damages to the ecosystem and resource availability are analyzed. The analysis of ecosystem damage includes the assessment

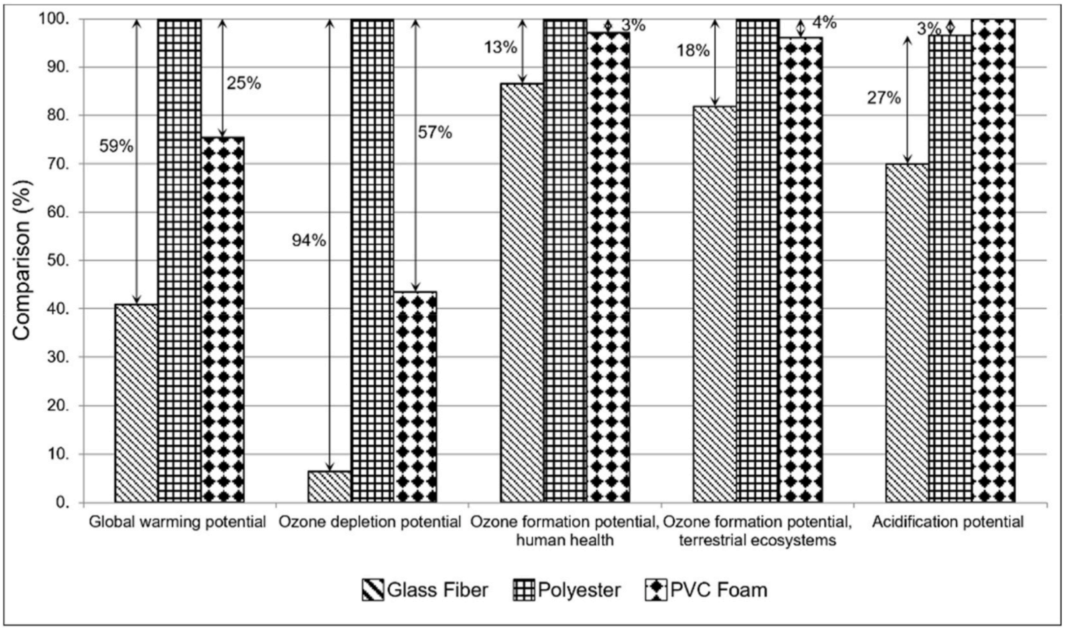

Fig. 9. Considering IMO regulations on the environmental midpoint index of each raw material.

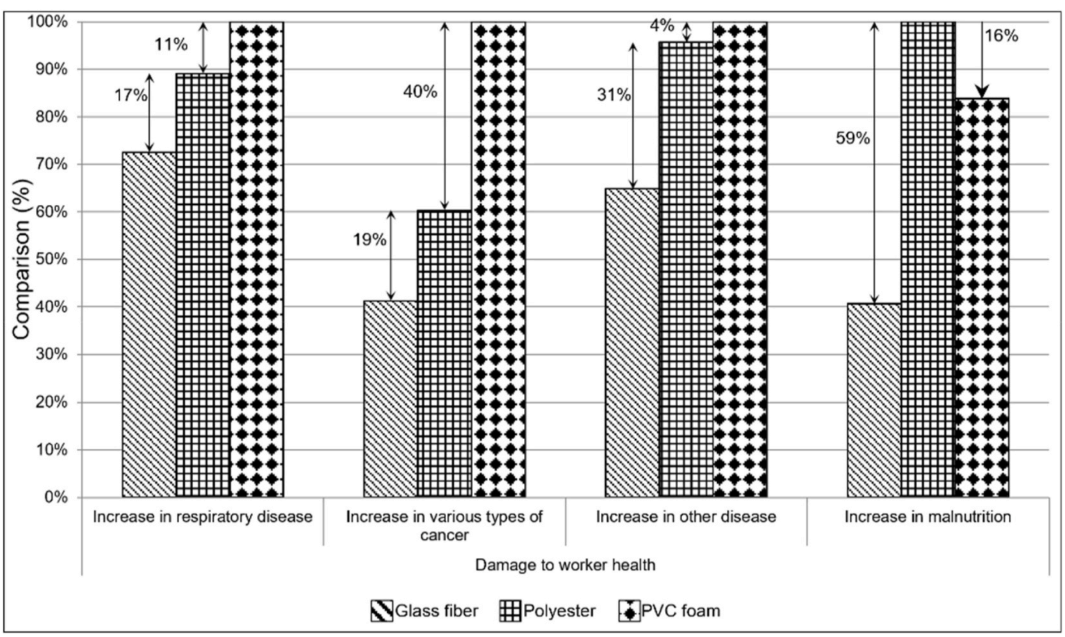

Fig. 10. Implication of each raw material on the toxicity of worker health.

of three indices: damage to freshwater, terrestrial species, and marine species. Additionally, the damage to resource availability was assessed by considering the increased extraction cost. Considering 1 kg of each raw material, as shown in Fig. 11, PVC foam showed the greatest impact on terrestrial and marine species. Polyester appeared to cause the most damage to freshwater and closely followed PVC foam in other indices. Regarding damages to resource availability, polyester resin incurred the highest extraction cost, with PVC foam closely following behind. Across all indices of damage, glass fiber was confirmed to emit the least impact.

7. Discussion

Generally, LCA studies are conducted in the ship operation phase (Dong and Cai, 2020; Hwang et al., 2020), while only a few studies are conducted in the manufacturing phase. The impact assessment results calculated based on the IMO regulations in the manufacturing phases are shown in Fig. 12. The result of the environmental impact was characterized as 100% of the maximum environmental impact. Across all impact index categories, single-skin laminates exhibited a greater negative environmental impact than sandwich structures, with a relatively large difference of approximately 38%–41%. When the raw material inputs were closely examined, further analysis revealed that single-skin laminates contain 2.3 times more polyester resin than sandwich laminates. Therefore, this difference contributed to the negative impact of the single-skin laminates on the environment in all categories compared to that of the sandwich structures.

In general, FRP which is mainly used of single skin laminates contain epoxy resin or thermosetting polymer has been found to have the most

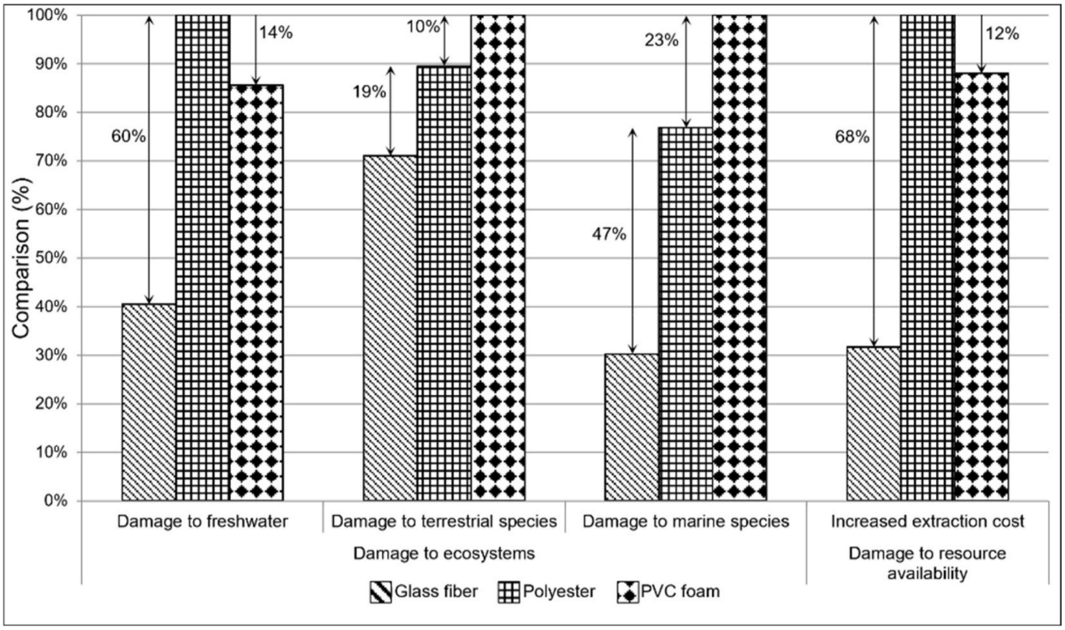

Fig. 11. Implication of each raw material on the damage to ecosystem and resources availibility.

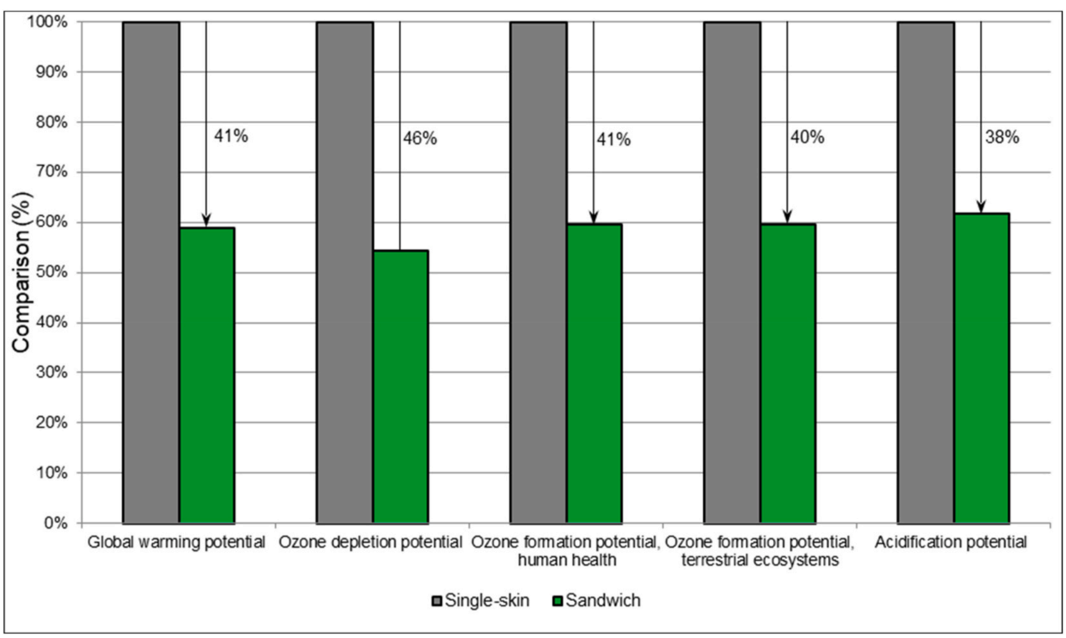

Fig. 12. Evaluation of the environmental midpoint index results for each structure in compliance with IMO Regulations.

significant impact on environmental impact that may leads to human health (Khalil, 2017). This study conducts a comparative analysis on single-skin laminates and other types of sandwich structures that utilize PVC foam as the core material, a third raw material. Not only does FRP harm human health, but it also adversely affects ecosystems and affects resource availability. As shown in Fig. 13, provides an overview of the overall allocation of damages between sandwich panels and single-skin laminates. In terms of all aspects of damages, sandwich panels offered greater benefits compared to single-skin laminates, as they contributed less to the overall damage.

Concerning the toxicity to worker health, applying a sandwich panel structure reduced the emission by approximately 39%–41% compared to the single-skin laminates. Upon detailed raw material, Thermosetting polymers, commonly known as resins, are considered hazardous chemicals and have been identified as carcinogenic to human health (Zaman et al., 2014). However, upon closer examination of the raw materials based on simulation, it was revealed that PVC foam poses the highest hazard, polyester resin is ranked second, and glass fiber has the least hazards (Fig. 10). Interestingly, PVC foam has 40% more carcinogenic elements, and 11% could cause more respiratory diseases compared to polyester resin. This underscores the higher risk of respiratory diseases and symptoms, including breathlessness and the potential for cancer, associated with increased exposure to PVC foam. Besides, in malnutrition indices, polyester resin has more bad impact compared to PVC foam. Additionally, an approximate reduction of 32%–41% in ecosystem damage was achieved by utilizing sandwich skin instead of a single-skin laminate. In the ecosystem damage pathways, the results indicate that polyester resin has most adverse effects on freshwater,

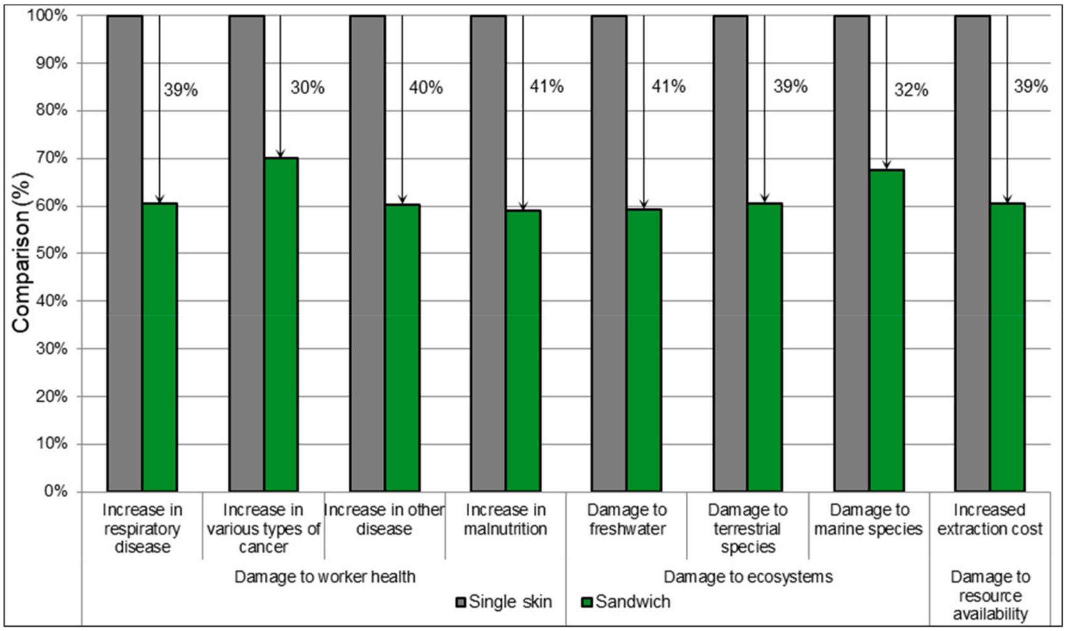

Fig. 13. Impact of each type of structure on damage endpoints.

while exposures to PVC foam lead to 23% higher species loss in water and 10% higher species loss in soil compared to polyester resin, highlighting its increased toxicity (Fig. 11). Finally, the selection of a sandwich panel instead of a single-skin laminate led to a 39% decrease in extraction costs, thereby reducing damage to resource availability.

When closer examination of the raw materials revealed that polyester resin, which is one of the most hazardous materials second to PVC foam, accounted for the largest portion of material input for single-skin laminates. These results clarified the reason that the single-skin laminate structure had a greater toxic impact on human health, damage to the ecosystem, and negative impact on resource availability compared to the sandwich structures. Meanwhile, the sandwich structure that used PVC foam, had relatively adverse effects on damage endpoint compared to glass fiber. However, the use of polyester resin, which had the greatest impact, was reduced by more than half. As a result, the damage endpoint index of the sandwich structure can be significantly reduced. In summary, sandwich structures incorporating PVC foam as the core material, despite being identified as the most hazardous to human health and harms ecosystems, show a significant reduction in hazardous factors and damage to ecosystem compared to single skin laminate. The quantity of resin in the sandwich structures which is nearly as hazardous as PVC foam, is decreased by more than half. Consequently, these findings position sandwich structures as a more sustainable choice for structures in FRP.

8. Conclusions

A comparative LCA and quantitative lightweight analysis were performed for two different ship structures: sandwich panels and single-skin laminates. The study analyzed the impact of raw materials during the manufacturing phase. The results of the comparison indicated that the sandwich structures were 42.44% lighter than the single-skin laminates, suggesting a significant weight reduction advantage over its counterpart.

Furthermore, when broken down into individual raw materials, PVC foam and polyester resin significantly impact the environment, leading to harmful effects on human health, and damage to ecosystems and resource availability. Therefore, the environmental indicators, particularly all damage endpoint indices, can be significantly reduced when using sandwich structures. Thus, it can be concluded that selecting a sandwich structure reduced the harmful toxicity to worker health by 39%–41%, mitigated damage to the ecosystem by 32%–41%, and alleviated damage to resource availability by 39% compared to the single-skin laminate. Equivalently, applying a sandwich structure with PVC foam as the core material can enhance the bending strength and reduce the thickness of the laminate skin, thus reducing the overall weight. Despite sandwich structures containing PVC foam being the primary cause of environmental damage, leading to impacts on human health and ecosystems, the quantity of polyester resin, which also has a high environmental impact, has been reduced by half. As a result, the sandwich structure still exhibits a considerable reduction in environmental impact compared to single-skin laminate and serves as one of the sustainable options. The findings of this study may influence the choice of composite material structures during the design phase, adding new considerations for structural selection. However, in current conditions, despite the numerous advantages offered by sandwich structures over single-skin laminates, they are not widely used in the industry due to their high design complexity and the potential for various failure modes in building. Additionally, the sandwich structure manufacturing process requires specialized skills and equipment, which results in higher production costs compared to single-skin laminate. The end-of-life phase of a product is a crucial aspect to consider, especially as FRP can be challenging to break down and may pose long-term harm to ecosystems. Comparison of different types of structures such as sandwich structures which lightweight effect has been confirmed and others effective disposal methods could be pursued to minimize environmental harm and find more sustainable options.

CRediT authorship contribution statement

Zhiqiang Han: Validation, Formal analysis, Data curation. **Jaewon Jang:** Methodology, Investigation, Formal analysis. **Jean-Baptiste R.G. Souppez:** Validation, Methodology. **Maydison:** Writing – original draft, Writing – review & editing, Software, Resources, Methodology, Investigation, Writing – original draft, Writing – review & editing, Software, Resources, Methodology, Investigation. **Daekyun Oh:** Writing – original draft, Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

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.

Data availability

The data that has been used is confidential.

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