STRUCTURAL CHALLENGES OF LOW-EMISSION VESSELS: A REVIEW

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SUMMARY

Increasing regulatory pressures to reduce shipping emissions have led to the design of low-emission vessels. These may rely on more sustainable propulsion and/or resistance reduction to reduce fuel consumption. However, the structural implications of such design strategies remain to be fully ascertained. This paper presents a review of the recent literature to identify the structural challenges associated with the next generation of sustainable vessels and tackles a range of available design options intended to reduce emissions. The results suggest that structural design has a fundamental role to play in enabling the application of low-emission design strategies on both small crafts and ships, but further developments in rules and regulations are necessary. It is anticipated these findings may support future regulatory advancements and may contribute to improvements in the design of sustainable vessels.

KEYWORDS

Structures; Structural Design; Sustainable Shipping; Low-Emission Vessels.

NOMENCLATURE

BOG	Boil-off gas
B_{WL}	Waterline breadth [m]
CCS	Cargo containment systems
CO_2	Carbon dioxide
EEDI	Energy efficiency design index
EEOI	Energy efficiency operational indicator
EEXI	Energy efficiency existing ship
FSI	Fluid structure interaction
GHGs	Greenhouse gases
IMO	International maritime organisation
LH_2	Liquefied hydrogen
LNG	Liquefied natural gas
L_{WL}	Waterline length [m]
NOx	Nitrogen oxides
SEEMP	ship energy efficiency management plan
SOx	Sulphur oxides
VSV	Very slender vessel

1. INTRODUCTION

Shipping and maritime transportation accounted for 90% of global goods transport and 3% of greenhouse gases (GHGs) emission in 2019 (Khan et al., 2021). Should no action be taken, this latter figure is forecasted to grow to 15% by 2050 (Van Themaat & Reuder, 2018), with other estimations being more pessimistic (Baxter, 2021). Consequently, increasingly stringent international regulation have been introduced by the International Maritime Organisation (IMO). These primarily focus on nitrogen oxides (NOx), sulphur oxides (SOx) and carbon dioxide (CO_2) (IMO, 2020). However, it is crucial to acknowledge that, while not covered in these regulations, emissions may also include noise, vibration, light and wash.

The introduction of an energy efficiency design index (EEDI) aims to achieve more eco-friendly vessels by design. Additionally, ship energy efficiency management plans (SEEMP) and energy efficiency operational indicators (EEOI) focus on operational measures. Lastly, an energy efficiency existing ship index (EEXI) came into force in November 2022 to cover existing vessels.

However, there remain many limitations to the EEDI, including its applicability to new builds only. Consequently, the majority of the commercial fleet will not be covered until 2040 (ITF, 2018). The targets are also deemed not challenging enough, poorly accounting for the developments in electrical technologies and wind assisted propulsion. Ultimately, the impact of the EEDI is seen as small (Smith et al., 2016). Nevertheless, regulations to achieve a sustainable shipping industry are a strong driver behind low-emission vessels.

The reduction of emissions and pollutants is directly related to the fuel consumption, itself linked to the power needed to achieve a given service speed, and thus the resistance of the vessel. Consequently, low-emission design strategies can be divided into two categories:

(i) those related to the generation of propulsive force, either through more sustainable fuel or alternative energy sources, and (ii) those associated with resistance reduction, thanks to hydrodynamic and material considerations. This is presented visually in Figure 1, while Appendix 1 offers a summary of the relevant publications associate with each design strategy. As such, a single degree of freedom is considered, namely surge: the drive force must equal the drag force to reach a given service speed.

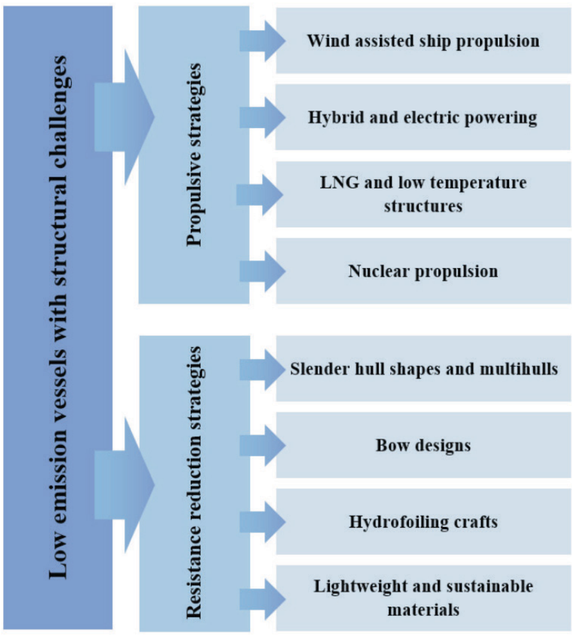

Figure 1. Graphical summary of the strategies for low-emission vessels yielding structural challenges

Despite the wide range of technologies available, only some yield significant structural design challenges. Nevertheless, these may be the main obstacle to their implementation on future ships. Consequently, an interest into the structural challenges of sustainable vessels has emerged (Wang & Pegg, 2022). The aim of this paper is to identify the challenges associated with the structural design of low-emission vessels in the recent literature to capture the latest developments, challenges and future opportunities.

The remainder of the paper is structured as follows. Section 2 tackles the structural challenges arising from propulsive strategies, namely wind assisted ship propulsion, hybrid and electric powering, low temperature structures, alternative fuels, and nuclear propulsion. Then, Section 3 discusses the impact on structural design of resistance reduction through means such as slender hull and multihull configurations, bow designs, hydrofoil crafts, and lightweight materials. Finally, Section 4 summarises the main findings of this paper.

2. STRUCTURAL CHALLENGES ASSOCIATED WITH PROPULSIVE STRATEGIES

2.1 WIND ASSISTED SHIP PROPULSION

Wind assisted ship propulsion has shown the potential to achieve in excess of 30% emission reduction (Bouman et al., 2017; Atkinson et al., 2018; Tillig & Ringsber, 2020; Khan et al., 2021). Emissions can also be suppressed by opting for a fully sailing vessel, making wind propulsion an attractive long term solution for sustainable shipping. The increasing use of wind assisted propulsion on commercial vessels is evidenced in Figure 21.

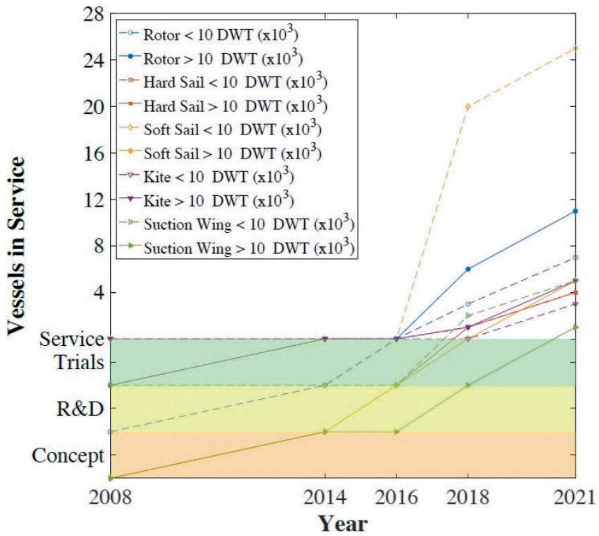

Figure 2. Wind-assisted vessels in service as of 2021 (Khan, et al., 2021)

Because of the rapid uptake of wind assisted ship propulsion, classification societies have developed new rules and regulations intended for wind assisted ships and their associated structure. Class NK first released Guidelines for Wind-Assisted Propulsion Systems for Ships (NKK, 2019), shortly followed by Det Norske Veritas Germanischer Lloyd's standard for Wind Assisted Propulsion Systems (DNV GL, 2019). In 2020, the American Bureau of Shipping detailed requirements for Wind Assisted Propulsion System Installation (ABS, 2020). Moreover, the Rules for Sail Assisted Ships (LR, 2020) published by Lloyd's Register identified basic structural requirements for the masts, posts and supporting structures. More recently, Bureau Veritas' Wind Propulsion Systems (BV, 2021) granted additional classification to vessels equipped with wind-assisted propulsion systems. The regulations combines environmental (wind, sea-state, and snow and ice), operating (sailing and out of operation) and system (intact and accidental) conditions. The interface between the ship and rigging is also considered, with a focus on local ship reinforcement as well as global hull girder strength.

Indeed, longitudinal strength requirements can be far greater than the conventional wave global loads (peak and trough landing) due to the compressive forces exerted by the rigging. Paakkari (2019), advocated for vessel-tailored support towers to be fully integrated with the ship's structure.

With the forecasted growth for wind propulsion, and as greater design experience and more sea trial/operational data becomes available, it is expected that the scope of the structural regulations will be extended and refined. Wind-assisted technologies can also benefit from the knowledge acquired in sailing yachts (DNV GL, 2018). This includes detailed regulations for rig loads (DNV GL, 2016; ISO, 2020), for which the same level of depth remains to be attained on wind-assisted propulsion systems.

Furthermore, while rig loads are well understood for sailing yachts, this is not the case for the various wind assisted propulsion configurations available. To reduce the heeling moment on ships, multi-masted or multi-rotored configurations are preferred to achieve the required sail area while retaining a low vertical centre of effort. Consequently, the interaction between multiple devices is critical. This prompted research into the forces generate by wind propulsion devices (Bordogna et al., 2019; Penloup et al., 2021; Reche-Vilanova et al., 2021; Souppez & Viola, 2021) as well as their interaction (Bordogna et al., 2018; Bordogna et al., 2020; Bordogna, 2020; Macklin, 2021), in order to support future developments in wind assisted propulsion and inherent regulations.

2.2 HYBRID AND ELECTRIC POWERING

While perhaps the most popular and well-established technologies in the transport industry, including shipping (Inal, et al., 2022), hybrid and electric propulsion have only been shown to trigger a few structural design considerations on ships. These primarily revolve around minimising the risk of damage to the battery bank, e.g. with a suitably delimited compartment, particularly in relation to watertight bulkheads (Alnes et al., 2017). There are also potentially higher risks due to collision, grounding and fire (Bolbot et al., 2019). The main structural challenge, however, resides in the added mass due to the batteries (Xing-Kaeding & Papanikolaou, 2021). Nevertheless, the literature does not suggest any specific structural arrangement to remedy this issue on hybrid and electric vessels. These, therefore, do not appear to raise particular structural design concerns.

2.3 LNG AND LOW TEMPERATURE STRUCTURES

There has been a sustained growth in the number of liquefied natural gas (LNG) vessels (Le Fevre, 2018) owing to the competitiveness and low cost of LNG (Li et al., 2020). Such vessels require special cargo containment systems (CCS) (Cadenaro et al., 2019). Moss-type tanks account for a third of the global LNG fleet, while the remainder are membrane-type CCS. LNG is stored on ships in liquid form at a temperature of −163°C. This low temperature yields specific structural challenges, including the brittle fracture of steel (Nikopoulou, 2017). There are also safety challenges related to fire and explosion (Erogov et al., 2019), and low-flashpoint liquids remain a regulatory issue (DNV GL, 2018).

The introduction of new types of CCS has resulted in novel structural implications. For instance, Strand (2019) discussed a new prismatic CCS, with a patented-protected configuration. This CCS does not form a part of the ship's hull, but instead depends on bulkheads and internal structures for strength. Relatively low-density foam is used for the insulation, giving better thermal performance than a higher compressive strength foam. This translates into low boil-off rates. Indeed, excessive boil-off gas (BOG) is a key problem on LNG bunkering vessels. Kim et al. (2020) presented a solution using and energy storage system, yielding BOG reduction from 46% to 15%, and greenhouse gas reduction from 17% to 5%.

Takaoka (2019) introduced the design and construction process of a new CCS, implemented on the first liquefied hydrogen (LH_2) carrier, also a low-temperature fuel. This CCS has a capacity of 1 250 m^3 and is located in the forward cargo hold, as shown in Figure 3. It is protected by a steel tank cover, with a vacuum multi-layer insulation system applied to the horizontal cylindrical pressure vessel. This independent tank (inner vessel) was supported by newly developed glass fibre reinforced plastic cylindrical pillars. The use of composite materials will be further detailed in Section 3.4(a) and shown to yield a significant reduction in structural mass.

The need for a reduced structural mass is accentuated on vessels that utilises a dual fuel gas turbine, able to use both diesel and natural gas, such as large commercial catamarans (Incat, 2022). This is twice as heavy as the equivalent diesel engine, which has a direct effect on the structural design of the vessel. Because of the increased static and dynamic oscillatory loads, more bracing and stronger foundations have been incorporated into the supporting hull structure. Accommodating LNG tanks also dictated sections of the demi-hull side walls had to be cut out for side entry. Hull frames therefore had to be removed, and the hull structure was redesigned to compensate for a reduction of bracing in this critical area. The complexity of the tank design leads to greater weight and further structural implications on the tank's supporting foundation. The increased displacement on LNG-powered vessels may therefore appear as a drawback.

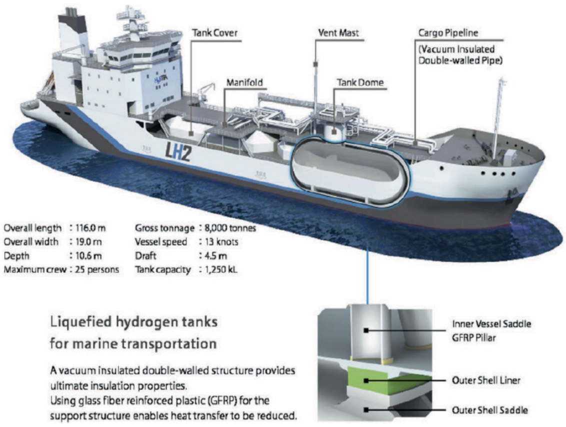

Figure 3. LH2 structural arrangement including composite support structure (Takoaka, 2021)

Consequently, this has prompted new developments in carbon fibre composite tanks, employing a resin that can withstand the required cryogenic temperatures, in itself a new area of focus in materials. These tanks do not suffer from corrosion or micro cracks and result in a weight saving of 85-90% for the same net volume when compared to steel. Other developments in tank structures for the purpose of reducing weight have been reported by Furukawa (2019), while Choi et al. (2018) proposed a plate-stiffened type prismatic pressure vessel, which differs from conventional cylindrical or spherical pressure vessels, and later confirmed this to be a viable option (Choi et al., 2020).

Low temperature structures are relevant to alternative fuels such as LNG or ammonia (Al-Aboosi et al., 2021). However, biofuels have also triggered interest (Wang et al., 2022), particularly as a short term solution enabling easy implementation onboard existing vessels. As such, this strategy is likely to be favoured in the short terms owing to the minimal retrofit required, as opposed to the majority of the strategies tackled in this paper.

2.4 NUCLEAR PROPULSION

While well-established for military crafts and certain icebreakers (Carlton et al., 2010), there has been a growing interest for nuclear propulsion on merchant ship owing to its power density (Petroski & Wood, 2014). Akin to hybrid and electric vessels (see Section 2.2), the structural considerations inherent to nuclear vessels reside in the protection of the onboard nuclear reactor in the event of an accident.

Carlton et al. (2011) identifies energy absorption of impacts, via the elasto-plastic collapse of the ship's structure as a primary design consideration. This represents a crumple zone able to provide energy absorption. Moreover, the reactor's compartment should be designed to ensure its structural integrity throughout the life of the vessel, thereby requiring a stringent fatigue analysis, and significant considerations for brittle fracture. The integrity of the reactor's compartment should also consider the risks associated with fire, and ensure the safety of the ship and environment with respect to the nuclear material carried onboard (Hirdaris et al., 2014).

Novel legislations are now emerging for nuclear merchant ships, with implementation as early as December 2022 (UK government, 2022), acknowledging the rapid development in this field, and the necessity to provide a clear regulatory framework.

3. STRUCTURAL CHALLENGES ASSOCIATED WITH DRAG REDUCTION

3.1 SLENDER HULL SHAPES AND MULTIHULLS

Slender hull shapes, defined as a high waterline length to waterline breadth (L_{WL}/B_{WL}), have been shown to reduce resistance, and therefore emission (Shuttleworth, 2012; Ridley et al., 2018). When applied to a monohull, this is referred to as a very slender vessel (VSV). While an overall reduction in drag is achieved, such crafts are associated with transverse stability issues, owing to their narrow B_{WL} and associated transverse second moment of area of the waterplane. Hence, multihulls have proven better suited to implement slender hulls across a range of applications (Yun et al., 2019), including small crafts (Ridley et al., 2018), military vessels (O'Rourke, 2017), and superyachts (Shuttleworth, 2012).

From a structural perspective, multihulls require certain global load cases to be considered for all vessel lengths, including small crafts (ISO, 2020). This is in contrast with monohulls, where global load cases are only recommended (i.e. not a regulatory obligation) for small craft in the following cases (Souppez, 2015; ISO, 2018): (i) high length-to-depth ratio, (ii) concentrated loads, such as rig loads, and (iii) low modulus materials in compression, the latter being relevant to some of the natural materials later discussed in Section 3.4(b).

Global loadcases for multihulls under 24 m are presented in the ISO 12215-7 (ISO, 2020). Six global load cases are defined: (i) diagonal load in quartering seas, (ii) rig loads, (iii) asymmetric broaching, (iv) longitudinal broaching, (v) longitudinal force on one hull, and (vi) crossbeam bending. The added structural load cases inherent to global strength and associated increase in scantlings and structural mass, however, do not outweigh the benefits of multihulls compared to monohulls.

Indeed, the case study of the superyacht Adastra (Shuttleworth, 2012) demonstrates a radical reduction in required engine power for a VSV and multihull configurations of comparable lengths and speeds. This is shown in Figure 4 compared to a reference semi-displacement monohull, where 100% corresponds to the value of the displacement, top speed, engine power and fuel consumption, respectively.

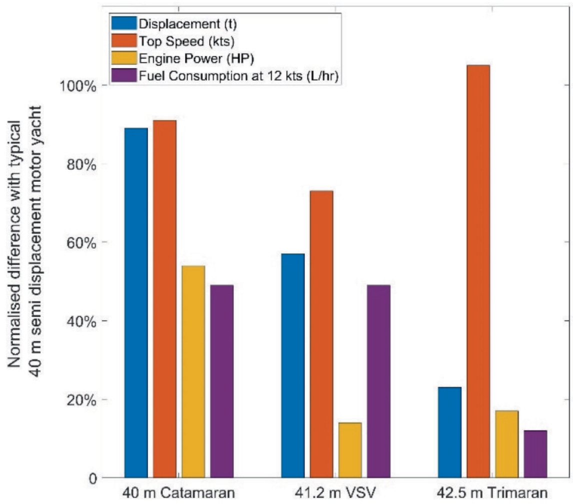

Figure 4. Performance of slender hull and multihulls. Data adapted from Shuttleworth (2012)

Figure 4 further reveals that a radical reduction in fuel consumption is achieved for identical displacements between a traditional monohull and the slender hull configurations presented, a trimaran yielding the highest reduction in fuel consumption. As a result, multihull configurations have been preferred for novel low-emission vessels employing alternative fuels and energy sources, This is the case of the Zero-V coastal research vessel (Madsen et al., 2020), which couples a trimaran hull configuration with hydrogen fuel-cell propulsion, although the latter did not yield structural implications in the design, as also evidence on catamarans (Pignone & Souppez, 2018).

3.2 BOW DESIGNS

Bulbous bows are a long-standing design feature intended to reduce fuel emission thanks to the destructive interference between the bulb's wave and ship's bow wave (Grote & Hefazi, 2021). This is now a common design feature, which can also easily be retrofitted. It typically leads to fuel savings of the order of 3-7% (Smith et al., 2016), and CO_2 emission reductions in the region of 2-5% (Tillig et al., 2015).

The design and construction of bulbous bows is well-established, particularly the vital relationship to the forward, watertight, collision bulkhead (DNV GL, 2016a). More recently, the structural considerations relative to bulbous bows have been focussed on ship collision (Liu et al., 2018; Liu et al., 2021) and slamming (Xie et al., 2020; Mustain et al., 2020), both critical design scenarios.

The same structural design considerations apply to other bow designs (e.g. Z-bow, inverted bow, axe bow) intended to minimize wave drag and maximise waterline length, thereby reducing the Froude number and consequently the resistance. Instances of such concepts have been investigated on multihulls high-speed patrol boats and navy ships (McGibbon & Rizvi, 2020; Kusuma et al., 2020).

3.3 HYDROFOILING CRAFTS

The recent literature on hydrofoiling vessels has focussed on the hydrodynamic aspects of high-performance sailing vessels, including small crafts (Andersson et al., 2018; Day et al., 2019), racing multihulls (Graf et al., 2020; Bagué et al., 2021; Cella et al., 2021; Prabahar et al., 2022; Patterson & Binns, 2022), and foil-assisted monohulls (Dewavrin & Souppez, 2018; Souppez et al., 2019; Horel & Durand, 2019; Borba Labi, 2019). However, a greater understanding of the load transfer into the hull structure remains an area requiring further work. On small vessels, the structural layout is closely linked to the general arrangement. Therefore, careful consideration must be taken into account to select a viable foiling technology for which the supporting structure will not overly interfere with the accommodation (Dewavrin, 2017). Moreover, regulatory bodies still consider hydrofoils to be beyond the scope of their regulations (ISO, 2019).

On commercial vessels, such as high-speed ferries, the hydrodynamics and drag reduction are well documented (Ruggiero & Morace, 2019), with a key issue identified for large metal foil structures, namely the thermal stresses associated with the complex welding process. Consequently, the foils become prone to high loads and fatigue issues. This would apply to both fully foiling vessels, as well as foil-assisted, or semi-foiling, where the hydrofoil provides an effective reduction in displacement without the vessel becoming fully airborne. As a result, drag and emission reductions are achieved, without incurring high slamming loads when coming of the foils, and without major seakeeping concerns. This has proven particularly attractive for wind farm support and crew transfer vessels.

While hydrofoiling vessels have proven a suitable low-emission alternative, due to the reduced drag, the benefits are far greater. One example is the lower wash generated, and therefore reduced erosion, vital in both natural areas as well as high-traffic waterways going through major cities. This prompted the development of hydrofoiling taxis (e.g., Sea bubbles (Kuiper, 2021)). Moreover, Li et al. (2019) investigated the acoustics of hydrofoiling vessels as a means to reduce noise and vibration, both affecting the marine life, thereby demonstrating the wide range of emission reduction that can be achieved with hydrofoils, beyond the typical scope of regulatory bodies limited to air and water pollutants (IMO, 2020).

However, there remain challenges with the structural design of hydrofoils, particularly as they outside of rules and regulations. The load path from the foil to the hull and supporting structure is critical to provision of suitable internal structure. The complexity is heightened by the deformation of the hydrofoils under operating loads. As a result, the use of fluid-structure interaction (FSI) is increasingly employed (Sacher et al., 2018; Pernod et al., 2019). This advanced level of analysis reveals the difficulty for regulatory bodies to implement a simplified scantling method at this point in time. The use of hydrofoils introduces new load cases, such as slamming loads resulting from the vessel 'crashing', i.e. abruptly coming off the foils. This is a new research area and methodologies are currently being investigated (Battley et al., 2020). The presence of hydrofoils also increases the risk of damage should a high-speed impact occur. Consequently, safety principles similar to that of rigs (ISO, 2020) are being implemented. The aim is to ensure the watertight integrity of the hull is maintained. This can be achieved with the introduction of a mechanical fuse or purposely designed sacrificial part of the foil, as commonly done with rigging. Nevertheless, the introduction of regulatory loadcases and design principles dedicated to hydrofoils would appear a necessary development to support their increasing use and implementation.

3.4 LIGHTWEIGHT AND SUSTAINABLE MATERIALS

Materials have proven benefits in reducing ship emissions. On the one hand, lightweight materials may contribute to reducing the structural mass and therefore the overall displacement. This then leads to a lower resistance and therefore lower emissions. On the other hand, sustainable and recycled materials significantly improve the lift cycle assessment of ships by reducing the overall carbon footprint and emissions over the product's life.

3.4 (a) Composite Materials

Composite materials are predominant in the small craft industry, employed in both leisure (Souppez, 2018) and commercial (Souppez & Ridley, 2017; Souppez, 2019) vessels. There is also a clear trend towards increasingly larger composite vessels (Lowde et al., 2022). However, there remains some reluctance to adopt composite materials on large (100 m+) vessels, which prompted the development of projects dedicated to tackling the use of composite for ships, namely Ramsses (2022) and Fibreship (2022). The latter demonstrated structural weight savings of up to 70% on an 86.4 m research vessel, 45% on a 244.8 m container carrier, and 36% on a 185.4m passenger vessel. These figure all include the added mass of fire insulation.

Indeed, the main counter argument to the adoption of composite has been the need for fire insulation in order to achieve the regulatory steel equivalency (LR, 2019), leading to added mass and cost. Today, composite ship structure, event with fire insulation, can be lighter than a steel equivalent (Fibreship, 2022). The weight savings ultimately reduce fuel consumption, making composite materials increasingly attractive for shipbuilding (Lee et al., 2021). The parametric study undertaken by Hakansson et al. (2018) also revealed significant weight savings due to the use of composites. These were further accentuated using carbon fibre over glass fibre, with the former consistently more expensive.

When looking at the overall life cycle assessment, Oh et al. (2019) showed that a 10% reduction in the mass of a 52 feet composite vessel yielded reductions in ozone layer depletion indicator and global warming indicator of 43% and 26% respectively, at the production stage. Additional work in composite structural design optimisation also showed the potential for a 27% reduction in structural weight on fishing vessels (Han et al., 2021). A larger meta-study by Bouman et al. (2017) indicated that CO_2 emission reductions of the order of up to 10% were realistically achievable by employing lightweight materials.

The literature identifies that further weight savings can be achieved with sandwich panels. The mechanical properties of the core, however, remain the limiting design factor. This prompted a heightened interest in foam cores (Jang et al., 2020), and the development of fatigue related data, such as S-N curves (Shen et al., 2017). Several key research questions inherent to composite sandwich constructions are yet to be answered, as discussed by Palomba et al. (2021). To alleviate some of the drawback of composite sandwich panels on larger vessels, all-metal sandwich structural arrangements have been implemented. These are common on larger ships, to offer the advantages of sandwich structures without the uncertainties inherent with foam cores. A typical mid-ship section of such a structural arrangement is depicted in Figure 5.

3.4 (b) Sustainable Materials

Contemporary sustainability concerns have made the eco-properties of materials, such as embodied energy and carbon footprint, novel considerations in addition to the traditional mechanical properties. The intention is to minimise the environmental impact over the life cycle of the vessel. Both natural fibres and timber have been shown to provide some of the lowest embodied energy per cubic meter while achieving a high Young's modulus and strength (Ashby, 2011).

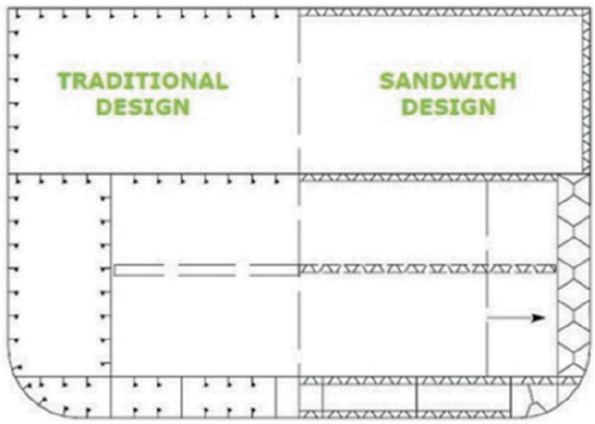

Figure 5. Traditional and sandwich section through a ship (Palomba et al., 2021)

Natural fibres have long been acknowledged as options in composite materials (Baley et al., 2021), with flax, hemp and jute being amongst the most commonly encountered. Despite renewed interest in recent years, natural fibres remain a very small part of the overall composite production. Natural fibres of animal origin are also available, but suffer from ethical concerns and limited production capabilities. Thus, they remain vastly unemployed. More recently, mineral fibres, such as basalt (a volcanic rock), have attracted research interest. The mechanical characterisation undertaken by Sri Lestari (2017) showcased the ability to replace fibre glass at a lower environmental cost.

A challenge to the wider adoption of natural fibre is the absence of default mechanical properties from regulatory bodies. This dictates the use of expensive experimental tests to quantify the mechanical properties in the absence of default regulatory values being provided, as is the case for glass, aramid, and carbon fibre (ISO, 2019; LR, 2019).

In addition to natural fibres for composites, there has been a strong resurgence of interest for the use of timber in boatbuilding (Souppez, 2020), motivating new considerations for regulatory compliance (Bucci et al., 2017; Souppez, 2020). Timber has been employed as part of the development of modern replicas (Alessio et al., 2016; Souppez, 2016; Thomas & Souppez, 2018) as well as new designs for both small crafts (Alessio Dos Santos, 2017; Guell & Souppez, 2018; Scekik, 2018) and IMO vessels (Linden & Souppez, 2018).

While the literature reveals a high interest and potential for timber construction for low-emission vessels, there remain two major obstacles. First, is the lack of reliable of mechanical properties (Souppez, 2021), raising a need for experimental testing to minimise safety margins and achieve a lighter structure. Secondly, there is limited coverage of wooden structures in rules and regulations. A heighten inclusion of both natural fibres and timber would therefore be recommended to facilitate the use of sustainable materials.

3.4 (c) Recycled Materials

The recycling of ships has markedly increased in recent years (Chowdhury et al., 2018), particularly in countries such as Bangladesh, where up to 90% of steel comes from recycled ships (Rabbi & Rahman, 2017). However, there are environmental challenges; for example, with emissions related to the dismantling and decommissioning (Raju & Prem Anandh, 2019). Consequently, a life cycle assessment approach is vital to ascertain the overall reduction in carbon footprint of ship recycling (Onal et al., 2020). The authors also revealed the importance of the hull shape and structural arrangement. Simpler geometries of ships proved better suited to recycling than the more complex geometries inherent to fishing and sailing yachts. Furthermore, experimental assessment of recycled composite has led to new experimental studies (Souppez & Pavar, 2023).

4. CONCLUSIONS

Increasingly stringent regulations on emissions and the ambition to address climate change have led to the development low-emission vessels. The structural implication of such vessels and their associated technologies remained to be characterized

This paper showed that, amongst the broad range of emission reduction strategies, only few incur a significant impact on structural design. However, those that do bring novel structural challenges that remain beyond the scope of regulatory bodies and class societies. As such, a thorough review of the recent literature has been undertaken.

Propulsive strategies such as hybrid, electric and nuclear power are primarily concerned with added structural integrity and safety. Wind-assisted ship propulsion presents major structural challenges and unconventional loadcases, many of which have been tackled for small sailing crafts, but not yet for ships. Lastly, low-temperature structures and liquids with low flashpoint remain to be fully covered by regulations.

On the other hand, emission reduction strategies relying on resistance reduction have also been shown to yield structural challenges, with multihulls requiring global loadcases considerations, and bow designs and hydrofoils requiring further attention to the integration with the overall structural arrangement. The latter, critically, remains absent from regulations. Several challenges were also highlighted for materials, particularly composites, resulting in tremendous structural mass savings on ships. The mechanical properties of sustainable composites, some foam cores, sustainable and recycled materials remain an area warranting further research work and future implementation as part of the relevant structural regulations. There may also be structural challenges that have not yet emerged. For instance, the use of air cavity chamber lubrication will see large recesses in the bottom of ship hulls, potentially featuring large external girders, and thus warrant investigations regarding the longitudinal strength of these vessels.

Structural design, therefore, has a fundamental role to play in enabling the application of low-emission design strategies. Moreover, there is a clear need for further regulatory developments in order to facilitate the adoption of the technologies underpinning low-emission vessels. It is anticipated that these findings may support targeted future regulatory advancements and may contribute to improvements in the design of the next generation of sustainable vessels.

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APPENDIX 1: SUMMARY OF REFERENCES FOR EACH DESIGN STRATEGY

Design Strategy		References
Propulsion	Wind Assisted Ship Propulsion	DNV GL, 2016 ; Bouman et al., 2017 ; Atkinson et al., 2018 ; Bordogna et al., 2018 ; DNV GL, 2018 ; Bordogna et al., 2019 ; DNV GL, 2019 ; NKK, 2019 ; Paakkari, 2019 ; ABS, 2020 ; Bordogna, 2020 ; Bordogna et al., 2020 ; ISO, 2020 ; LR, 2020 ; Tillig & Ringsber, 2020 ; BV, 2021 ; Khan et al., 2021 ; Macklin, 2021 ; Penloup et al., 2021 ; Reche-Vilanova et al., 2021 ; Souppez & Viola, 2021.
	Hybrid and Electric Powering	Alnes et al., 2017 ; Bolbot et al., 2019 ; Xing-Kaeding & Papanikolaou, 2021 ; Inal, et al., 2022.
	LNG and Low Temperature Structures	Nikopoulou, 2017 ; Choi et al., 2018; DNV GL, 2018 ; Le Fevre, 2018 ; Cadenaro et al., 2019 ; Erogov et al., 2019 ; Furukawa, 2019 ; Strand, 2019, Takaoka, 2019 ; Choi et al., 2020 ; Kim et al., 2020 ; Li et al., 2020 ; Al-Aboosi et al., 2021 ; Takoaka, 2021 ; Incat, 2022 ; Wang et al., 2022.
	Nuclear propulsion	Carlton et al., 2010; Carlton et al., 2011 ; Hirdaris et al., 2014 ; Petroski & Wood, 2014 ; UK government, 2022.
Drag Reduction	Slender Hull Shapes and Multihulls	Shuttleworth, 2012 ; Souppez, 2015 ; O'Rourke, 2017; ISO, 2018 ; Pignone & Souppez, 2018 ; Ridley et al., 2018 ; Yun et al., 2019; ISO, 2020 ; Madsen et al., 2020.
	Box Designs	Tillig et al., 2015 ; DNV GL, 2016 ; Smith et al., 2016 ; Liu et al., 2018 ; Kusuma et al., 2020 ; McGibbon & Rizvi, 2020 ; Mustain et al., 2020 ; Xie et al., 2020 ; Grote & Hefazi, 2021 ; Liu et al., 2021.
	Hydrofoiling Crafts	Dewavrin, 2017 ; Andersson et al., 2018 ; Dewavrin & Souppez, 2018 ; Sacher et al., 2018 ; Borba Labi, 2019 ; Day et al., 2019 ; Horel & Durand, 2019 ; ISO, 2019 ; Li et al., 2019 ; Pernod et al., 2019 ; Ruggiero & Morace, 2019 ; Souppez et al., 2019 ; Battley et al., 2020 ; Graf et al., 2020 ; IMO, 2020 ; ISO, 2020 ; Bagué et al., 2021 ; Cella et al., 2021 ; Kuiper, 2021 ; Prabahar et al., 2022 ; Patterson & Binns, 2022.
	Lightweight and Sustainable Materials	Ashby, 2011 ; Alessio et al., 2016 ; Souppez, 2016 ; Alessio Dos Santos, 2017 ; Bucci et al., 2017 ; Rabbi & Rahman, 2017 ; Shen et al., 2017 ; Souppez & Ridley, 2017 ; Sri Lestari, 2017 ; Chowdhury et al., 2018 ; Guell & Souppez, 2018 ; Hakansson et al., 2018 ; Linden & Souppez, 2018 ; Scekik, 2018 ; Souppez, 2018 ; Thomas & Souppez, 2018 ; ISO, 2019 ; LR, 2019 ; Oh et al., 2019 ; Raju & Prem Anandh, 2019 ; Souppez, 2019 ; Jang et al., 2020 ; Onal et al., 2020 ; Souppez, 2020 ; Baley et al., 2021 ; Han et al., 2021 ; Lee et al., 2021; Palomba et al., 2021; Souppez, 2021 ; Fibreship, 2022 ; Lowde et al., 2022 ; Ramsses, 2022 ; Souppez & Pavar, 2023.