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Review of advanced composite structures for naval ships and submarines

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Abstract

The recent applications of fibre-reinforced polymer composites to naval ships and submarines are reviewed. Since the mid-1980s the use of composites has increased considerably as the military strive to reduce the acquisition and maintenance costs and improve the structural and operational performance of naval craft. A wide range of new applications of composites to naval vessels are described, including their current and potential use in the superstructures, decks, bulkheads, advanced mast systems, propellers, propulsion shafts, rudders, pipes, pumps, valves, machinery and other equipment on large warships such as frigates, destroyers and aircraft carriers. Potential applications of composites to submarines are also described, such as their possible use in propulsors, control surfaces, machinery and fittings. The growing use of composites in the complete construction of fast patrol boats, minehunting ships and corvettes is discussed. For each application the major benefits gained from using composites instead of conventional shipbuilding materials, such as steel and aluminium alloys, are identified. The paper also outlines the main drawbacks of using composites in naval vessels. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Advanced composite structures; Naval ships; Naval submarines

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1. Introduction

This paper reviews recent advances in the development of composite structures for future naval ships and submarines. Currently there is a wide range of naval structures being developed using fibre-reinforced polymer composites. This development is driven by the need to enhance the operational performance (e.g. increased range, stealth, stability, payload) but at the same time reduce the ownership cost (e.g. reduced maintenance, fuel consumption costs) of warships and submarines. The applications examined include large patrol boats, hovercraft, minecountermeasure vessels and corvettes that are built completely of composite material. Other new or potential uses for composites are in the superstructures, advanced mast systems, bulkheads, decks, propellers, propulsion shafts and rudders for large surface combatants such as frigates and destroyers. In submarines, the future applications of composites may include control surfaces, propulsors and mast systems. Navies are also exploring the feasibility of using composites for internal equipment and fittings, such as machinery, heat exchangers, equipment foundations, valves, pumps, pipes and ducts.

While composites are now being considered for a diverse range of naval applications, for many years these materials were used only in a few non-critical ship structures and in small boats. Composites were first used immediately after the Second World War in the construction of small personnel boats for the US Navy. These boats proved to be stiff, strong, durable and easy to repair, and these attributes led to a rapid expansion of composite use in other types of US naval craft between the mid-1940s and 1960s. By the time of the Vietnam War there were hundreds of such personnel boats, river patrol boats and landing craft as well as several reconnaissance craft in-service amounting to over 3000 composite craft. The US Navy also used composites in deckhouses for small ships, masts for some communication ships, piping for destroyers, and fairwaters and casings for submarines. Table 1 lists the naval applications for composites by the start of the Vietnam War. Numerous articles review these earliest applications of composites to the US Naval craft [1–14].

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Table 1
Composite naval applications between World War II and Vietnam War

- Minesweeper (15.5 m long)
- Landing craft (15.2 m)
- Personnel boat (7.9 m)
- Sheathing of wood hulls
- Submarine sonar dome
- Submarine fins
- Masts and mast shrouds
- Rudders
- Tanks (fuel, lube oil, water)
- Torpedo tubes
- Hatch covers
- Landing craft reconnaissance (15.8 m)
- River patrol boat (9.5 m)
- Pilot boat
- Submarine fairwater
- Submarine non-pressure hull casing
- Deckhouses for small ships
- Radomes
- Antenna trunks
- Piping
- Crew shelters
- Rope guards

During the 1950s other navies began to install composite structures on their ships and submarines. The Royal Navy and French Navy began to use composites instead of steel in bow sonar domes for submarines to provide better acoustic transparency, and a similar use was for radomes to protect communication and surveillance antennae on surface ships [11,15–18]. By the 1970s minehunting ships were being built of composites for the Royal Navy, Royal Swedish Navy and Norwegian Navy and the Dutch Navy started to build pilot boats and landing craft of composite [8,19–25]. This period marked the beginning of the application of composites to large naval structures.

Many reviews have been published on the application of composites to naval vessels, although all were published over eight years ago and some are more than 30 yr old [8,11,13,14,16,21,26,27]. The purpose of this paper is to provide an overview of recent developments in advanced naval composite structures, with emphasis given to the progress made since the mid-1980s. The paper provides a description of the benefits and limitations of using composites in place of conventional ship building materials such as steel and aluminium alloy. The current stage of development of new composite structures is discussed, and the types of naval ships that may be fitted with these structures are described. Because a large variety of naval composite structures are under development, a short description of each application is given for the sake of brevity. More detailed information is available in the articles referenced in this paper. The review is based on information published in the open literature. Those applications classified by defence organisations are not reviewed for reasons of security.

2. New developments in composite naval vessels

Early uses of composite materials were in the construction of small patrol boats and landing craft. The relatively poor fabrication quality and low stiffness of the hulls restricted these naval craft to less than about 15 m in length and 20 tonnes in displacement. In recent years the improved design, fabrication and mechanical performance of low-cost composites has led to an increase in the use of composites for large patrol boats, hovercraft, minehunters and corvettes. Fig. 1 presents the results of a survey on the length of naval vessels built entirely of composite between the years 1945 and 2000. Lengths have increased steadily with time, and currently there are all-composite naval ships up to 80–90 m long. If this trend continues, aided by improvements in the technology, then hulls for mid-sized warships, such as frigates that are typically 120–160 m long, may be constructed from composites from about 2020. This is unlikely, however, unless cost of building ships with composite is less than for steel construction. This section reviews the latest developments in all-composite naval patrol boats, minecountermeasure vessels (MCMV) and corvettes and briefly describes the use of composites in naval hydrofoils.

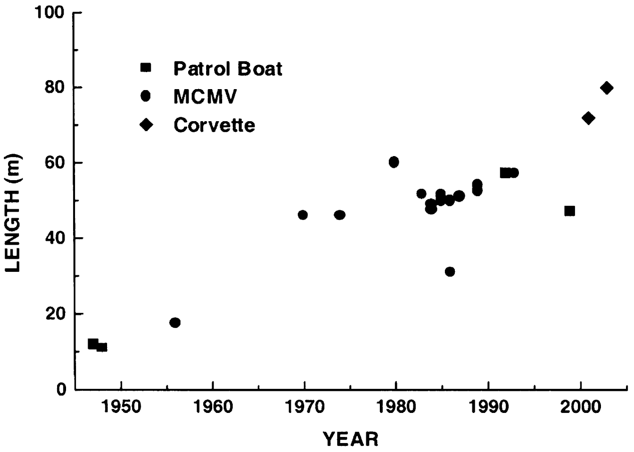

Fig. 1. Plot of vessel length against year of construction for all-composite patrol boats, MCMV and corvettes. Source of data: Sharpe [28].

2.1. Patrol boats

Composites have been used for the construction of naval patrol boats for nearly 40 years. The first all-GRP patrol boats were built for the US Navy in the early 1960s, and were used on rivers in the Vietnam War [9]. During the 1970s and 1980s the use of composite materials in small patrol boats gradually increased and currently there are over 300 boats in-service. Most GRP patrol boats are less than 10 m long and 10 tonnes displacement, and they are rarely built longer than about 20 m because of their low hull girder stiffness. Hulls for patrol boats longer than 25 m are usually built using aluminium alloy or steel. Because of their small size, composite patrol boats are usually confined to patrolling in-land waterways and coastal waters, and cannot be relied upon for offshore patrol operations.

Nevertheless, many countries are now showing an interest in building all-composite patrol boats up to ~55 m in length and 300 tonnes in full-load displacement for offshore operations. Feasibility studies have compared the cost, weight and structural performance of large patrol boats made using steel, aluminium or sandwich composite [24,29–31]. The studies find that the structural weight of a patrol boat made of GRP sandwich composite material should be ~10% lighter than an aluminium boat and ~36% lighter than a steel boat of similar size [24,30]. Use of the latest fabrication techniques such as Seeman composites injection moulding process (SCRIMP) or by using carbon fibre reinforcement may provide further savings in hull weight [24,29]. Designers expect the reduced hull weight to allow an increase in military payload, provide greater range and/or reduced fuel consumption. Goubalt and Mayes [30] predict that the cost of operating a composite boat will be less than for a steel design because of reduced maintenance (due to less corrosion) and lower fuel consump- tion. Calculated life-cycle costs of a composite boat are slightly less (~7%) than for a steel boat of the same size.

A major problem with building ships with composites is the low hull girder stiffness. Makinen et al. [24] estimate that a 50 m long patrol boat made of sandwich composite will experience hull girder deflections that are up to 300% higher than for a steel boat. Similarly, Alm [32] calculates that the hull girder deflections will be about 240% higher when a 50 m long naval vessel is built of composite rather than steel. The increased hull deflection may cause problems such as fatigue cracking around joints and connections and may cause misalignment in the propeller shaft-line.

The largest all-composite naval patrol boat is the Skjøld class vessel operated by the Royal Norwegian Navy (Fig. 2). The Skjøld is an air surface effect ship with a catamaran hull form that is 46.8 m long, 13.5 m wide and 270 tonnes full-load displacement. Water jets propel the patrol boat and lift fans reduce the draft to 2.6 m to achieve a top speed of 57 knots in calm water and 44 knots in Sea State 3. The Skjøld is built entirely of a sandwich composite consisting of glass- and carbon fibre laminate skins with a poly(vinyl chloride) foam core. The first patrol craft, *KNM Skjøld*, was commissioned in 1999, and is currently undergoing sea trials. If successful, the Royal Norwegian Navy will consider purchasing a further six patrol boats [33–37].

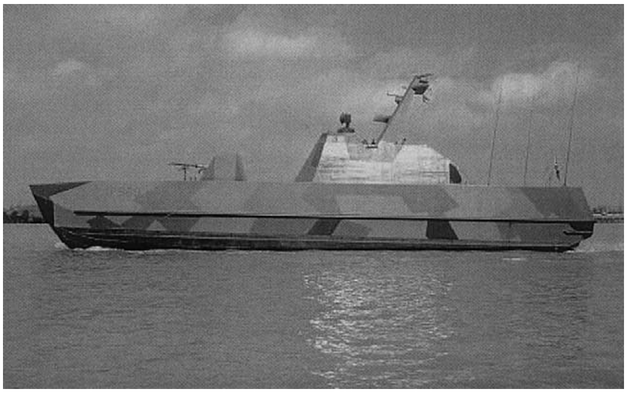

Fig. 2. The Skjøld class patrol boat.

Skjøld's boat builders used a sandwich composite instead of steel or aluminium alloy because they found it simplified the construction of the hull and superstructure. The composite also provides a high strength-to-weight ratio, good impact properties and low infrared, magnetic and radar cross-sectional signatures. When using only GRP materials it is necessary to incorporate conducting materials (e.g. copper mesh) to provide electromagnetic shielding to sophisticated electronic equipment used on the boat which adds to the construction cost. Extensive use of carbon laminates gives the required high stiffness in structures such as beam frames, mast and support base to the gun. The carbon fibre used in the superstructure also provides some electromagnetic shielding. The Skjøld has been fitted with an array of 56 fibre Bragg grating sensors to provide real-time information on the strain levels generated during sea trials [38].

The Royal Swedish Navy is also using composites in the construction of large patrol craft. In the late 1980s the Swedish Navy built a 30 m long surface effect ship, known as the Smyge MPC2000, from sandwich composite material. The composite consists of carbon, glass and Kevlar fibre-vinyl ester skins and a poly(vinyl chloride) foam core. These materials were selected to achieve a good balance of desirable properties. They provide light-weight, excellent corrosion resistance, good damage resistance against underwater shock loading, and a number of stealth properties including low thermal and magnetic signatures and good noise-dampening properties [24,39]. Despite the construction of the Skjøld and Symyge MPC20000, most large patrol boats continue to be built using steel and aluminium alloys because of their lower cost.

2.2. Minecountermeasure vessels

Naval ships designed for locating and destroying sea-mines are known as minecountermeasure vessels (MCMV). Traditionally these vessels were made of wood because its non-magnetic properties allow the ships to operate in waters protected by magnetic sea-mines. The high-quality timber needed to build MCMV has become increasingly scarce since the Second World War, so driving up construction costs to a level where wood is no longer economical. MCMV built of wood also have high through-life costs because of their need for ongoing

Table 2
Survey of GRP minecountermeasure vessels in-service or under construction as at 31/12/1999

MCMV class	Navy	Number of vessels[a]	Hull design	Length (m)	Full load displacement (t)	Refs.
Hunt	United Kingdom	13	Framed single skin	60	750	[28,42,43]
Sandown	United Kingdom	8 + 4	Framed single skin	52.5	484	[28,45]
Al Jawf (Sandown)	Saudia Arabia	3	Framed single skin	52.7	480	[28]
Segura (Sandown)	Spain	2 + 2	Framed single skin	51	530	[28,46]
Erdian (Tripartite)	France	13	Framed single skin	51.5	605	[28,47–49]
Alkmaar (Tripartite)	Netherlands	15	Framed single skin	51.5	595	[28,47,48]
Flower (Tripartite)	Belgium	7	Framed single skin	51.5	595	[28,47,48]
Pulau Rengat (Tripartite)	Indonesia	2	Framed single skin	51.5	568	[28,46]
Munsif (Tripartite)	Pakistan	3	Framed single skin	51.5	595	[28]
KMV	Belgium	0 + 1	Framed single skin	52.0	644	[28,50]
Landsort	Sweden	7	Sandwich composite	47.5	360	[28,51–55]
Bedok (Landsort)	Singapore	4	Sandwich composite	47.5	360	[28]
Styrso (YSB)	Sweden	4	Sandwich composite	36.0	175	[28,46]
Flyvefisken (Standard Flex 300)	Denmark	5	Sandwich composite	54.0	480	[28,55,56]
Oksøy/Alta	Norway	9	Sandwich composite	55.2	375	[28]
Bay	Australia	2	Sandwich composite	30.9	178	[28,57,58]
Lerici	Italy	4	Monocoque	50.0	620	[28,45,59,60]
Gatea	Italy	8	Monocoque	52.0	697	[28,45,59,60]
Mahamiru (Lerici)	Malaysia	4	Monocoque	51.0	610	[28]
Lat Ya (Gatea)	Thailand	2	Monocoque	52.5	680	[28]
Osprey (Gatea)	USA	12	Monocoque	57.3	930	[28,45,59,60]
Huon (Gatea)	Australia	2 + 4	Monocoque	52.5	720	[28,46]
Swallow (Lerici)	South Korea	6 + 7	Monocoque	50.0	520	[28]
Lerici	Nigeria	2	Monocoque	51.0	540	[28,59]
Yevgenya	Azerbaijan	2	Unspecified	24.6	90	[28]
Yevgenya	Bulgaria	4	Unspecified	24.5	90	[28]
Yevgenya	Cuba	8	Unspecified	24.6	90	[28]
MPMB	Croatia	1	Unspecified	25.7	90	[28]
Modified SAV	Denmark	6 + 10	Unspecified	23.9	125	[28]
Swiftships	Egypt	3	Unspecified	33.8	203	[28]
Kuha	Finland	6	Unspecified	26.6	90	[28]
Mahe (Yevgenya)	India	6	Unspecified	24.6	90	[28]
Yevgenya	Iraq	2	Unspecified	24.6	90	[28]
Goplo	Poland	13	Unspecified	38.3	225	[28]
Mamry	Poland	4	Unspecified	38.3	225	[28]
Yevgenya	Russia	15	Unspecified	24.6	90	[28]
Yevgenya	Syria	3	Unspecified	24.6	90	[28]
Yevgenya	Ukraine	1	Unspecified	24.6	90	[28]
Yevgenya	Vietnam	2	Unspecified	24.6	90	[28]
Yevgenya	Yemen	5	Unspecified	24.6	90	[28]

[a] In cases when two numbers are shown (e.g. 8 + 4) then the first number gives the number of vessels in-service while the second number gives the number of vessels under construction.

maintenance. To overcome the need to use wood, [1] in 1951 the US Navy attempted to build a 15.5 m long minesweeper, known as the XMSB-23, with a honeycomb sandwich composite [9,10]. However, the fabrication quality, mechanical performance and water resistance of the composite was poor. As a result seawater seeped into the hull of the XMSB-23, and therefore the vessel could not be used for mine countermeasure operations.

Design and development of composite minehunting ships continued in the USA [40,41] and UK [15,16,19,20] during the 1960s and 1970s. The first MCMV successfully built using composites was *HMS Wilton* in 1973, which at 46.6 m long and 450 tonnes full-load displacement was then the largest all-GRP ship [20,42]. The outstanding success of *HMS Wilton* led to a rapid expansion in the use of composites, and since the early 1980s over 200 all-composite MCMV have been constructed. Table 2 lists the different types of MCMV currently in-service or under construction and many are over 50 m long with displacements at full load exceeding 600 tonnes.

This use of composites in MCMV has driven the innovation of ship hull designs that are able to resist local buckling, provide high hull girder stiffness and excellent underwater shock resistance. Naval operators also consider other criteria in selecting hull types, including

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[1] Wood is still used in the construction of some MCMV, although it is common practice to cover timber hulls with a glass-reinforced polyester (GRP) sheath [21].

acquisition and through life maintenance costs together with magnetic signature, acoustic damping and fire performance properties [22]. The hull structures most commonly used on MCMV are known as framed single-skin, unframed monocoque, and GRP-sandwich. Fig. 3 shows examples of ships built with these designs.

The most common hull type is the framed single-skin design. The Royal Navy's Hunt and Sandown class MCMV have this structure [42–45]. Likewise the Tripartite (Eridan, Alkmaar and Flower classes) ships used by the French, Netherlands and Belgian Navies, respectively, are built in the same manner [47,49]. The design consists of transverse frames and longitudinal composite girders that are adhesively bonded in the transverse and longitudinal directions to a pre-laminated GRP hull. This framing system provides the required hull girder stiffness, and is shown schematically in Fig. 4 [21,42–45,64,65].

Monocoque construction does not utilise a hull-framing system. Instead an extremely thick skin (up to 0.15–0.20 m) of GRP is used to obtain the required hull stiffness and underwater shock resistance [21,45,46,

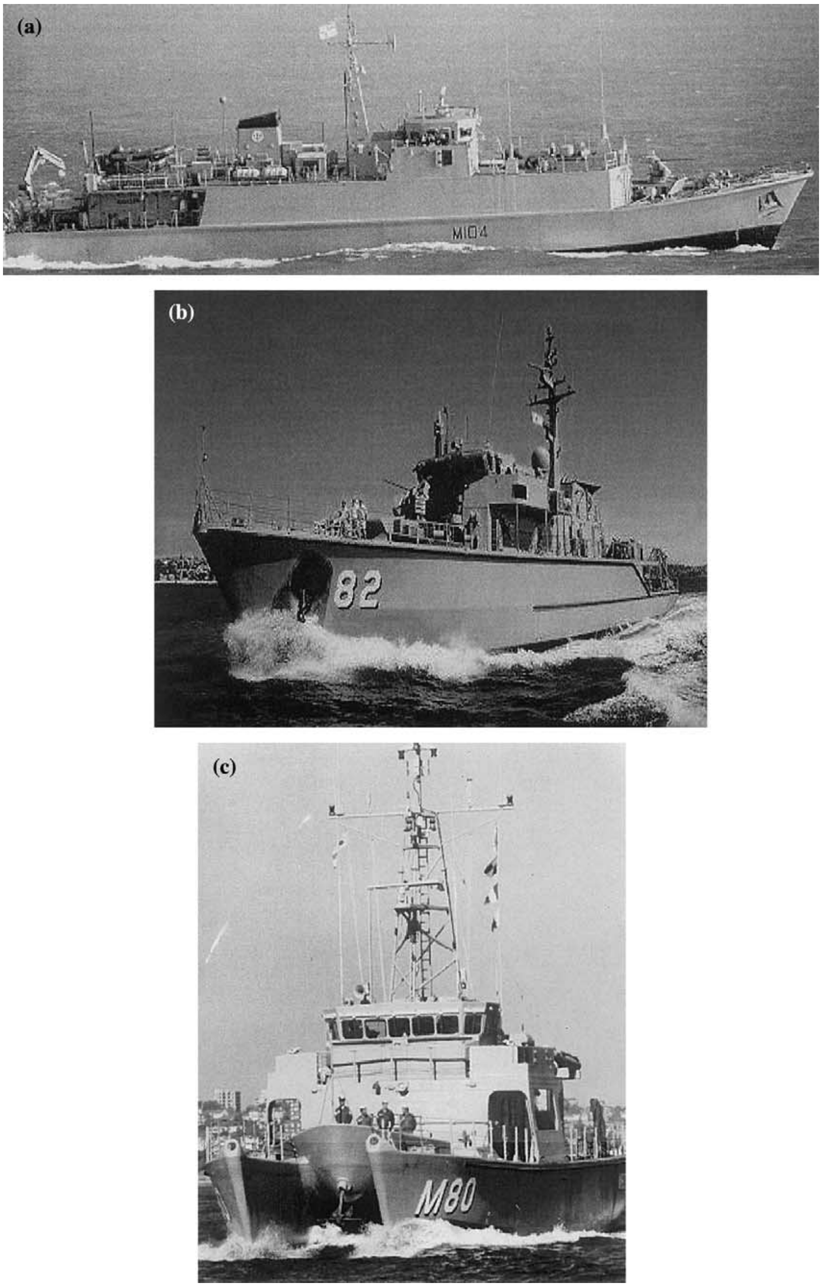

Fig. 3. (a) Sandown. (b) Huon and (c) Bay class MCMV that have hull types of single-skin framed, monocoque and sandwich composite, respectively.

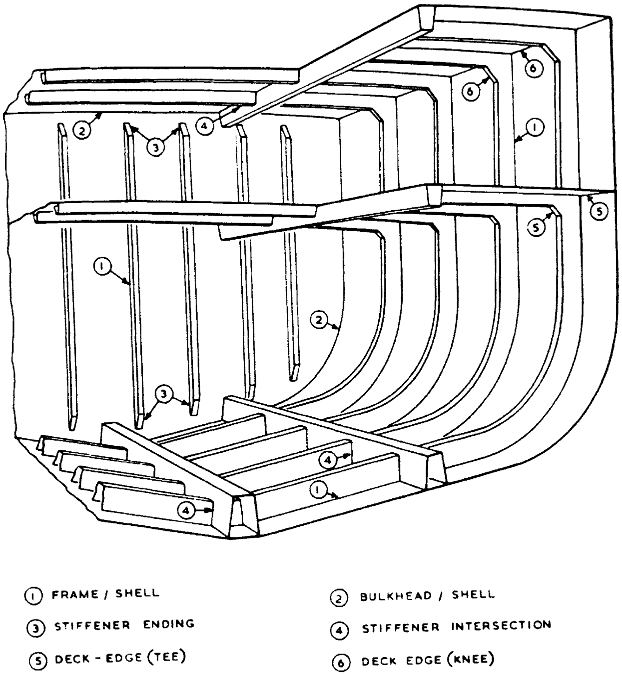

Fig. 4. Schematic of the framed single-skin hull design for composite ships From Smith [21].

59–63]. The decks and main bulkheads also contribute to the stiffness of monocoque ships. Examples of MCMV built with a monocoque hull are the Italian Lerici and Gatea class minehunters. Huon class (Australia) and Osprey class (USA) are similar vessels based upon the Italian design.

The GRP sandwich hull structure has gained wide acceptance through its use in the Landsort and Flyvefisken (Standard Flex 300) MCMV [24,51–56,65]. The hull and superstructure are constructed from a sandwich composite composed of thin GRP face skins covering a thick core of poly(vinyl chloride) foam. The skins are designed to give high stiffness and strength while the core provides high shear resistance and low weight.

Other composite hull types have been developed for MCMV, although are not widely used as yet. For example, Gass et al. [66] assessed a corrugated GRP hull as a prototype for use in MCMV. The external surface has longitudinal corrugations designed to provide higher stiffness and strength to the hull girder while being $\sim$25% cheaper to fabricate than the conventional framed single-skin design. Despite the potential benefits, no MCMV have been built with a corrugated hull design.

During the 1980s the US Navy assessed the feasibility of building MCMV with an air cushion surface effect hull form [67]. They expected the vessel to have lower magnetic and acoustic signatures and less susceptibility to underwater shock due to the small wetted area of the hull that would lead to safer operation. The project was terminated before a ship was built. However, the Royal Norwegian Navy recently commissioned the air cushion surface effect ships Oksøy and Alta class MCMV. These vessels are catamarans built from GRP-sandwich composite. One of the Oksøy class ships, KNM Hinnøy, is also unique as an MCMV. It is the only one fitted with fibre optic (Bragg grating) sensors to monitor strains in parts of the hull and deck [68–71]. The sensors were installed to confirm that the structural behaviour of the ship agreed with the design predictions, and for hull-condition monitoring to provide a warning of structural overload. Other sensors have been installed to monitor structure-borne vibrations generated by the engine, water jet propulsors and other machinery.

2.3. Corvettes

The longest naval ships currently being built from composite material are corvettes. The Royal Swedish Navy is leading the design and construction of composite corvettes through their YS-2000 project [23,39,72–79]. The project aim is to produce the Visby class corvette, which at 72 m long, 10.4 m wide and a full-load displacement of 620 tonnes, is the longest and nearly the heaviest all-composite naval ship (Fig. 5). The Visby class is designed to be a multi-purpose vessel with capabilities for surveillance, combat, mine laying, mine countermeasures, and anti-submarine warfare operations. To undertake these roles, the vessel must be lightweight, strong, resistant to underwater shock loads, and stealthy by having low radar and magnetic signatures. The Royal Swedish Navy considered that these requirements could be achieved more readily by constructing the entire ship with composite materials rather than with steel, aluminium alloy or a mixture of materials.

The Visby corvette is built from sandwich composite panels having face skins of hybrid carbon- and glass

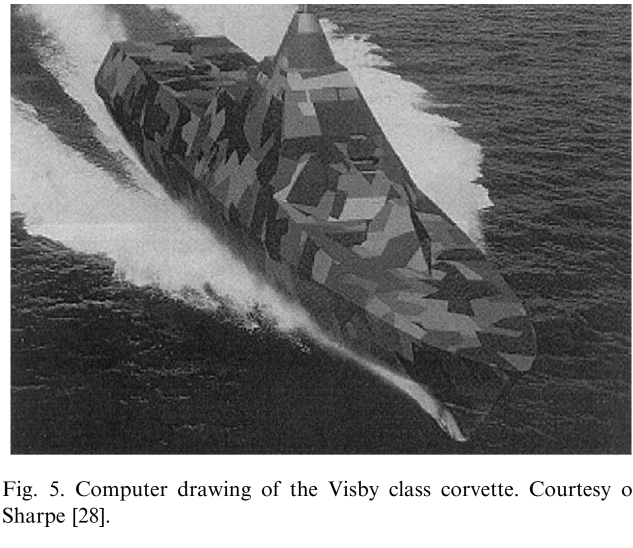

Fig. 5. Computer drawing of the Visby class corvette. Courtesy of Sharpe [28].

fibre polymer laminate covering a poly(vinyl chloride) foam core. The Visby is the first naval ship to make significant use of carbon fibre composite in the hull. Carbon fibres are at least five times more expensive than glass fibres, which has limited their use in large naval composite structures. However, the design studies for the Visby showed that using some carbon fibres in the composite skins would reduce the hull weight by about 30% and did not greatly increase the fabrication cost. The weight saving translates to improved ship performance by increasing the range of the corvette and lowering operating costs by reducing fuel consumption. A further benefit of using carbon-reinforced composites is that the fibres provide adequate electromagnetic shielding in the Visby superstructure. There are however a number of problems with using composites, such as poor fire resistance. The first Visby class corvette was launched in June 2000 and will undergo two years of sea-trials. The Royal Swedish Navy has ordered a further five vessels.

The Royal Singapore Navy is presently designing with Kockums AB of Sweden a new generation patrol vessel/corvette, known as the NGPV class, which will be made of composite material. Construction has yet to commence, although it is planned that eight vessels will be made. No design details have been published, but it is known that the ship has a stealth design with a trimaran hull that is expected to be made of sandwich composite material. Some structures on the ship will be made from Kevlar composite for improved resistance to small arms fire and shrapnel. The ship is expected to be 80 m long with a displacement of 1016 tonnes, which will make it longer and much heavier than the Visby corvette [39].

The US Navy is also considering using composite materials in their next-generation corvettes [31,80,81]. Preliminary design studies looked at the feasibility of building warships up to 85 m long and 1200 tonnes displacement using composite instead of steel. They conclude a reduction in structural weight of up to ~30%, a reduction in full-load displacement of 7–21%, and a cost saving of up to 15% is achievable. The reduced hull weight has the potential to improve the warfighting capability of the corvette through higher weapon payloads or increased operational range. Vosper Thornycroft (UK) is assessing the feasibility of making all-composite corvettes or metal-hull corvettes with the superstructure, bulkheads and masts made of composite [82]. The Swedish Navy are expected to commence soon the design of a 90–120 m long warship built entirely of sandwich composite material [78]. Despite the significant progress made over the past 10 years in the design and construction of composite corvettes, it is expected that most corvettes will continue to be built of steel over the next decade because of lower construction costs.

2.4. Hydrofoils and hovercrafts

Composites have been used in small amounts in naval hydrofoils and hovercraft since the 1970s. Graner [12] has reviewed the early applications of composites to these craft for non-critical structures to reduce weight. Recently the use of composites in hovercraft has expanded to include primary structures, such as the superstructure and hull. For example, in 1998 the Sri Lankan navy commissioned a 18.8 m long M10 class hovercraft having a superstructure made of Kevlar fibre-reinforced composite [28]. A prototype 20 m long naval hovercraft is under development in Sweden with the hull built of sandwich composite. Hovercraft builders are using composite instead of aluminium alloy, which is the conventional hull material, to reduce weight, improve damage tolerance and reduce maintenance [77]. However, Smith and Monks [29] estimate that using composite materials instead of aluminium alloy will increase the construction cost of the hull by about 15%.

3. Composite superstructures

Topside structures of naval boats have been constructed of composite materials for many years. Composites have been used in deckhouses of patrol gunboats since the mid-1960s and in superstructures of minehunting ships since the early-1970s [6,8,11]. More recently, the Royal Finnish Navy fitted a superstructure made of sandwich composite to the aluminium hull of the fast patrol boat, Rauma [83,84]. Composite deckhouses on boats overcome two major problems seen with those built in steel, namely corrosion and high topside weight. Thus a weight-saving of up to 65% is achieved for small naval craft (less than 20 m long) by replacing steel with composite materials [11].

In contrast, the means of reducing topside weight of large warships has in the past been by building superstructures from aluminium alloy. However, battlefield experience, most notably the Falklands War, have highlighted the poor fire resistance of aluminium alloy superstructures which have high thermal conductivity and soften and melt at relatively low temperatures. Furthermore, aluminium alloy superstructures can experience severe fatigue cracking where welded to a steel hull, and also high up in the structure where strains induced by hull girder bending are greatest. Cracking has become so persistent and widespread in many warships that expensive repairs are regularly required. Reinforcement of crack-prone regions with composite has been used to suppress cracking, although this is an expensive solution [85,86]. In some cases, ships have been taken permanently out-of-service [21,87–89]. Because of these problems many navies are now assessing the feasibility of building large ship superstructures with composite. The yield strain of GRP is about 10 times that of steel, hence the incidence of fatigue cracking in a composite superstructure on a steel hull is expected to be considerably less.

The feasibility of fitting a composite superstructure onto the steel hull of a large warship was first explored in the mid-1980s. Since then many feasibility studies have been performed, with most concluding that the best design options are to construct the superstructure with single-skin composite panels stiffened by a steel frame, or with top-hat stiffened sandwich composite panels [21,88–104]. The studies also showed that a composite superstructure should be 15–70% lighter than a steel superstructure of a similar size. The weight-saving that can be achieved is highly variable because it is dependent on the type of composite and the amount of steel framing. Predictions of weight saving on the next-generation frigates for the Royal Norwegian Navy with composite superstructures instead of steel are about 180 tonnes [102].

Replacing elements of a steel superstructure with composite can also considerably reduce the topside weight. For example, the Royal Navy estimated that replacing the all-steel helicopter hanger on their Type 23 frigate with a hybrid composite panel/steel frame structure would achieve a weight saving of 31% (or 9 tonnes). Dodkins and Williams [104] report that replacing the steel superstructure of a medium-sized frigate with a composite structure reinforced with steel frames will only provide a modest weight saving while significantly increasing the construction cost. However, Dodkins and Williams [104] suggest that an all-composite superstructure built with stiffened sandwich composite panels will provide the greatest weight saving ($\sim$40%) without greatly increasing the construction cost. The reduced topside weight would provide increased weapons payload and better sea-keeping. Despite the high weight saving compared with steel, composite superstructures are about 30% heavier than similar structures made from aluminium.

Ship superstructures made of composites have a number of disadvantages compared to steel and aluminium alloy. The cost to construct in composite can be much higher than with metal because composite superstructure sections are expensive to connect to a steel deck. For example, Høyning and Taby [102] estimate that using composite instead of steel in the superstructure of a medium-sized frigate will increase the construction cost by 40–140%, depending on the materials, framing system and required level of radar signature reduction. Dodkins and Williams [104], on the other hand, estimate that composite superstructures will be only 9–47% more expensive than those made of steel. Planning predictions for composite superstructures on Arleigh Burke (DDG-51) destroyers and Type 23 frigates are more expensive than steel structures by about 18% and 35%, respectively. Despite the cost penalty, some ship builders and navies are beginning to accept high construction costs because of the potential cost-savings obtained using composites over the life of a vessel. Savings through the life of the ship are anticipated to be due to reduced maintenance and repair costs and increased ship availability due to a reduction in fatigue cracking [87,102]. However a further problem is that many shipyards are neither equipped nor skilled to fabricate complex superstructure sections from composites.

The French Navy is the first to operate large warships fitted with a composite superstructure [87,105–107]. France launched its first La Fayette frigate in 1992 and its Navy currently has five in-service with another one to be commissioned in 2002. This frigate is built with the aft section of the superstructure made of GRP-sandwich composite panels (Fig. 6). The aft section, which includes the helicopter hanger, is 38 m long, 15 m wide, 6.5–8.5 m high from the main deck, and weighs 85 tonnes, which makes it the largest composite super-

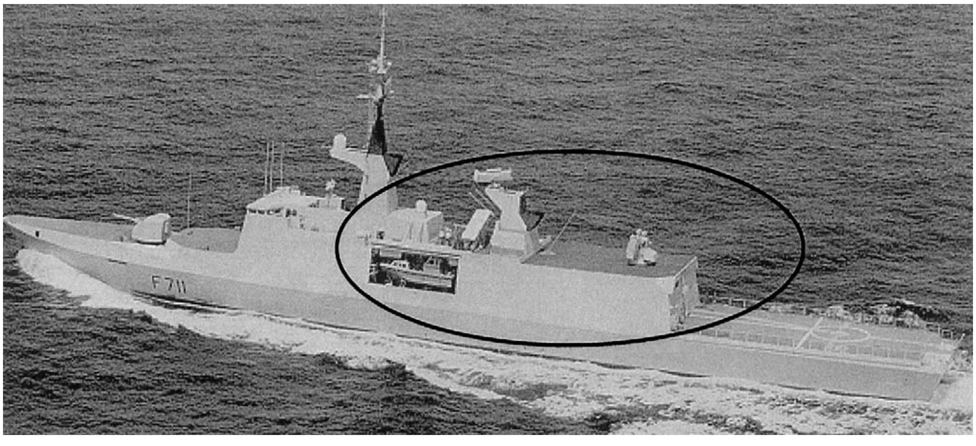

Fig. 6. La Fayette frigate with the composite superstructure section. Courtesy of Sharpe [28].

structure on a warship. Funnels on the frigate are also made of composite material. The fore section of the superstructure, that includes the wheel house, combat information centre and telecommunications control centre, is made of steel. The Taiwanese Navy has six La Fayette frigates (Kang Dang class) while Saudi Arabia will have three modified La Fayette frigates (Type F-3000S) by 2005.

While the La Fayette class frigate is currently the only large warship with a composite superstructure, the US Navy is looking into integrating sections of sandwich composite within the steel superstructure of the Arleigh Burke class (DDG-51) destroyer. Sections that may be made of composite include the close-in weapons systems (CIWS) enclosure, Forward Director's Room, helicopter hanger, hanger doors and funnels. The US Navy was also considering building the deckhouse to the Grasp class (ARS51) salvage ship with composite. Similarly, the Royal Navy is looking into constructing helicopter hangers for the Type 23 and next-generation frigates with composite. Vosper Thorneycroft are designing sandwich composite superstructures for steel-hulled corvettes and patrol vessels [104]. The Royal Norwegian Navy is also assessing the feasibility of composite superstructures to their next-generation frigates [102]. With the success of the composite superstructure on the La Fayette frigate and other developments for medium-sized warships (from 1000 to 6000 tonnes), future possibilities are that part or all of the topside to destroyers and aircraft carriers will be built of composite material [87].

4. Composite masts

Composites were first used in masts in the 1960s when steel masts aboard US Navy communications ships, *USS Wright* and *USS Saipan*, were replaced with GRP masts that stood 10–25 m high [6,11]. Conventional steel truss masts, with their open structure and protrusions, are a source of interference to the ship's own radar and communication systems. Steel masts also increase the radar signature and are prone to corrosion.

Renewed interest in composite masts for warships occurred in the early 1990s. A study by Critchfield et al. [94] in the early 1990s showed that composite masts could overcome many of the problems experienced with steel masts. A one-half scale, 11 m tall prototype truss mast was constructed of a hybrid composite containing S2-glass fibres for maximum ballistic performance and carbon fibres for high stiffness. They found that a composite mast would be 20–50% lighter than an aluminium mast of the same size. The composite mast was also expected to have better fatigue resistance, eliminate corrosion, and improve the performance of mast sensors by reducing electrical blockages compared to a steel mast of similar size. The composite mast was also able to meet the US Navy requirements for vibration, air blast and ballistic damage resistance. However, this feasibility study found that a composite mast would be about 50% more expensive to build than an aluminium alloy mast [94].

The US Navy embarked on the Advanced Enclosed Mast/Sensor (AEM/S) project in 1995 to develop the future-generation of ship masts [108–111]. The AEM/S project was an advanced technology demonstration aimed to prove that composite masts could be built for large warships at an affordable cost. It was also used to confirm improved corrosion resistance, sensor performance and lower radar cross section. The AEM/S system was installed aboard the Spruance class destroyer *USS Arthur W. Radford* as a replacement for her steel truss main (aft) mast in May 1997. The *USS Arthur W. Radford* and a close-up view of the composite mast is shown in Fig. 7. The difference between the forward steel truss mast and the aft composite mast show exactly how far the design of the AEM/S system departs from conventional mast structures.

The AEM/S system is 28 m tall and 10.7 m in diameter, which makes it the largest composite topside structure on a US Navy ship. The mast was built using a frequency selective hybrid composite material configured in a hexagonal shape. This unique design allows the passage of the ship's own sensor frequencies through the composite structure with very little loss while reflecting other frequencies. In this way the performance of the antennas and other sensors is improved while the radar cross-section of the mast is reduced. Another benefit is that the mast structure encloses all major antennas and other sensitive electronic equipment, so protecting them from the weather and thereby reducing maintenance. The performance of the AEM/S system on the *USS Arthur W. Radford* has met all the requirements set by the US Navy. This success of the AEM/S system is a major advance towards the merging of advanced composite mast technology into the topside design for the next generation of US Navy surface combatants [110,111]. They are currently considering installing the AEM/S system on future destroyers (SC 21), aircraft carriers (CVX), sea-lift vessels (LH(X)), and the San Antonio class Amphibious Transport Dock *USS San Antonio* (LPD-17) as well as in major upgrades of masts on existing warships.

In 1996 the Royal Navy and Vosper Thornycroft (UK) started to develop an Integrated Technology Mast (ITM) made of composite material. This project has similar objectives to the AEM/S project in that the ITM is designed to overcome many of the problems associated with conventional steel-truss masts. The ITM is a sandwich composite structure fabricated with

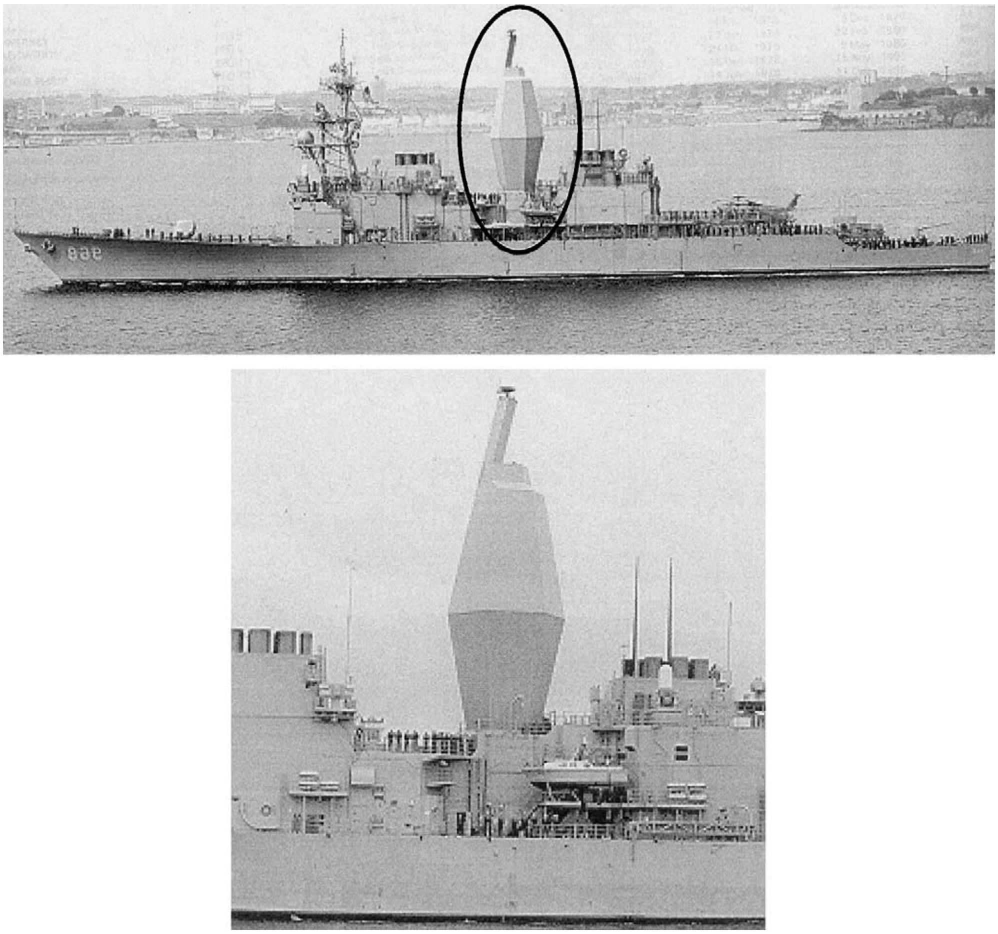

Fig. 7. USS Arthur W. Radford showing the AEM/S system. Courtesy of Sharpe [28].

radar absorbing materials that contain communication and surveillance antennas and embedded sensors. Some of the anticipated advantages of their composite mast include improved stealth, better environmental protection and reduced electromagnetic interference to sensors. Also a 10–30% reduction in weight compared to a conventional steel mast of similar size. The ITM is being developed for the *Sea Wraith* stealth corvettes and the Royal Navy's post-2012 Future Surface Combatant and the Future Aircraft Carrier [112,113]. Composite masts may also be installed retrospectively on some Halifax class patrol frigates operated by the Canadian Navy.

5. Composite propulsion systems

5.1. Propellers

Propellers for naval ships and submarines have traditionally been made of nickel-aluminium-bronze (NAB) alloy because of its excellent corrosion resistance and high yield strength. There are a number of problems associated with the properties of NAB. The material is expensive to machine into the complex shape of a propeller blade. NAB propeller blades are prone to fatigue-induced cracking and have relatively poor acoustic damping properties that can lead to noise problems from vibration. Problems such as these have led naval architects to assess the feasibility of fabricating propeller blades with materials other than NAB alloys. The most notable alternate materials are stainless steel, titanium alloy, sonaston and composites.

The design and performance of composite propeller systems for naval vessels is highly classified information, and therefore recent developments are not reported in the open literature. It is widely known, however, that composite blades are designed with the fibres aligned to support the major hydrodynamic and centripetal loads. A benefit of using composites is that the load-bearing fibres can be orientated in different directions along a blade to minimise strain. As a result, the performance of a blade can be optimised through the alignment and stacking sequence of fibres. Lin and

Lin [114] show that the alignment direction of the fibres affects the thrust, effective pitch ratio and camber of propeller blades, and therefore careful design and fabrication of the blade is needed to ensure optimal performance. Composite blades are made as a solid laminate containing glass and carbon fibres or as a sandwich construction. A thin layer of polyurethane, NAB or stainless steel may be used to protect the blade tips from severe impact damage. The composite blades are usually adhesively bonded and bolted to a metal propeller hub, although composite hubs have also been developed [115–119].

The early development and performance testing of composite propellers are described by Ashkenazi et al. [116]. A first use for composite propellers up to 2 m in diameter was in Soviet fishing boats during the 1960s, and continued with propellers up to 6 m on large commercial ships in the early 1970s. A prototype composite propeller for hovercraft was also developed in the early 1970s [115]. Extensive trials were performed in the USSR to compare the performance of composite with metal propellers having the same geometry. The tests were performed on propellers with diameters between 0.26 and 3 m fitted to commercial ships with displacements of 2–5000 tonnes travelling at speeds of 5–35 knots. Ships fitted with composite propellers were virtually equal in performance to vessels with metal propellers in respect to speed, fuel consumption, engine workload, absorbed horsepower and operating life. Furthermore, composite propellers reduced the magnitude of the resonance vibrations in the engine and propeller shaft by about 25%, resulting in less hull vibration and noise [116]. The potential benefits of composite propellers are summarised in Table 3, although it is important to recognise that some of these have not yet been proven. The drawbacks of composite propellers include higher fabrication cost, larger blade tip deflections and lower impact damage resistance compared with NAB propellers.

A variety of naval vessels have been fitted with composite propellers for testing and evaluation, such as landing craft and minesweepers [117,120–123]. Composite propellers are also used on Mark 6 torpedoes [124,125] and small boats [118,126]. However, despite the potential benefits of composite propellers, they are not widely used in naval vessels. The only exception is the Viksten minesweeper of the Royal Swedish Navy that has a three-bladed single-screw composite propeller.

Table 3
Benefits of composite propellers for naval vessels

Reduced fabrication cost (but only if a large number of blades are manufactured)
Reduced through-life maintenance costs
Reduced wear on gearbox/shaft
Weight savings
Improved vibration damping properties
Improved fatigue performance
Reduced corrosion
Increased cavitation inception speeds by using thick and flexible blades
Lower electrical/magnetic signatures
Lower noise signatures

Computer modelling studies by Lin [127,128] indicate that certain types of composite propellers have inferior hydrodynamic performance. Lin [127,128] used finite element analysis techniques to compare the performance of a propeller blade made of a low-modulus sandwich composite material against a NAB blade with the same geometry. The maximum deflection at the blade tip under hydrodynamic load conditions was an order of magnitude higher for the composite propeller. Similarly, Kane and Dow [119] calculated that the maximum blade tip deflection was five times higher when a propeller was made from glass fibre composite rather than NAB alloy. The lower stiffness of composite is the cause of the greater deflection. Lin [127,128] also showed that the maximum in-plane bending and shear stresses in their sandwich composite blade were roughly 50% higher than in the NAB blade. Thus the composite blade could reach its maximum working stress at ship speeds well below those for a NAB blade. The findings apparently contradict those results from the trials on composite propellers that were described above. However, a low-modulus composite material was modelled. Propellers designed for commercial and naval ships are usually made from much stiffer carbon fibre composites that experience smaller blade tip deflections [115,119, 121,123].

5.2. Propulsors

Composite propulsors have several advantages compared to metal propulsors. They may reduce life-cycle cost, lower mass and magnetic/electric signatures, suppress radiated noise and have better corrosion resistance and fatigue performance. Much secrecy surrounds the development of composite propulsor rotor blades for naval submarines. While it is known that propulsors of various sizes up to several metres are under development, the design and performance details are classified [122]. The French Navy is expected to fit the Le Triomphant class submarines with a composite shroud over a 2.7 m diameter metal propulsor.

5.3. Propeller and propulsion shafts

Accompanying the advances in composite propellers and propulsors in recent years are developments in composite shafts for warships and submarines. The enormous steel propulsion shafts on large ships such as frigates and destroyers account for up to 2% (or ~100–200 tonnes) of the total ship weight. Shafts made from carbon fibre/epoxy and glass fibre/epoxy composites have the potential to be 25–80% lighter than a steel shaft of similar size [125,129–133]. Ship designers expect a composite shaft to also suppress the transmission of noise from machinery and propellers due to the intrinsic damping properties of composite materials. Hence the acoustic signature of the vessel would be reduced. Being non-magnetic, composite shafts will also reduce the magnetic signature of a vessel. It is anticipated that composite shafts will have fewer problems associated with corrosion, bearing loads and fatigue, and lower life-cycle costs by at least 25% [125,129,131,132,134].

The development of composite propeller shafts is not as advanced as for many other naval structures described in this paper. The US Navy successfully tested a prototype carbon/epoxy shaft on a patrol vessel (YP-654 class) in the 1980s [129]. They are also considering replacing the 20 tonne, 10 m long, 0.68 m diameter steel propeller shaft proposed for the Sacramento class support ship with a composite shaft that is up to 80% lighter and possibly 50% cheaper to fabricate [125,129]. Norway has composite propeller shafts fitted to its Skjøld and Rauma 2000 classes of fast patrol boat [36,37]. Despite these applications, many design, fabrication, performance, durability and maintenance issues need to be resolved before composites can be considered as strong candidate materials for propeller shafts in naval ships and submarines.

6. Composite secondary structures, machinery and fittings for naval ships

6.1. Background

Interest is growing in the use of composites for secondary structures, fittings and equipment in naval ships. The applications include funnels, bulkheads, decks, rudders, hatch doors, engine foundations, pipes and ventilation systems. Also included are mechanical components for diesel engines, pumps and heat exchangers. This section describes these different applications.

6.2. Funnels

It is highly probable that composites will be used increasingly in the exhaust funnels of large warships to reduce topside weight and, possibly, cost. For many years, there has been a successful use of composite funnels on MCMV. More recently sandwich composites are in use for the stacks of the Visby class corvette and La Fayette class frigate [106]. Work is in progress to make large warship funnels with sandwich composites, with the US Navy considering installing composite stacks on the Arleigh Burke (DDG51) class destroyer. Funnels made from composite rather than steel improve the stealth of naval ships by reducing the radar signature. Infrared (thermal) signature is also reduced because of the excellent thermal insulation properties of sandwich composites.

Published information on the weight and cost savings that can be achieved using composite materials in warship funnels is not available. However, Horsman [95] reports that fitting composite funnels to two Italian cruise liners provided a weight saving of 50% and cost saving of 20% compared with the aluminium and stainless steel funnels that were replaced.

6.3. Bulkheads, decks, doors and hatches

The feasibility of fitting steel naval ships with composite bulkheads, decks, watertight door and hatches is under investigation [95,96,104,125,135,136]. Fig. 8 shows a composite bulkhead fabricated by Vosper Thornycroft (UK) using SCRIMP. The potential benefits include a weight saving of 20–40%, lower magnetic signature, lower rate of heat transmission to adjacent compartments in the case of a fire, and better sound damping than steel structures [96]. A drawback is that composite bulkheads are expected to be 20–90% more expensive to fabricate and install than steel bulkheads. Similarly, composite decks are predicted to be 30–45% more expensive than steel decks [96]. Much of the increased cost involves fitting joints for attaching the composite bulkheads to the surrounding steel structure that provide adequate damage resistance against internal blast. Until the costs are reduced, it is unlikely that bulkheads and

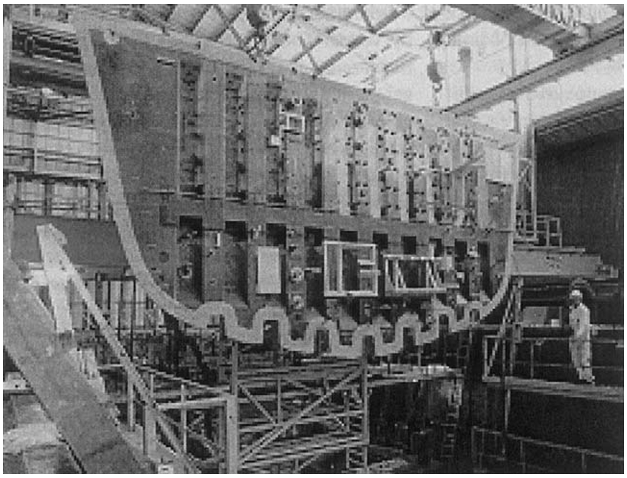

Fig. 8. Composite bulkhead manufactured by Vosper Thornycroft (UK) using the SCRIMP process.

decks made of composite will be in common use on large naval ships.

6.4. Enclosures and shields

Several navies are considering composites for use in weapons enclosures, dry deck shelters and as missile blast shields to provide greater protection against high-speed projectiles and shrapnel [95]. The US Navy has already used Kevlar composite armour on their Kidd class-guided missile destroyers for personnel protection against small arms fire.

6.5. Rudders

Composite ship rudders are being developed because they are expected to be up to 50% lighter and 20% cheaper than existing metal rudders. The US Navy is using composite rudders on their Avenger class mine-countermeasures vessels [95,137].

6.6. Machinery and engine components

The US Navy was first to investigate the use of composites in ship engines in an evaluation of gear cover casings made of GRP. The composite cases were more corrosion-resistant and 90% lighter than a conventional steel case. However, because they radiated more noise than the steel cases the composite casings were never used [4]. More recently, the US Navy has been appraising the possible use of composites in a large number of components for engine room machinery, as shown in Fig. 9. Glass-reinforced phenolic composites have been considered for the block, head, oil pan, cam cover, water pump, oil pump, pulleys, idler and timing sprockets of ship diesel engines. The potential benefits of using composites instead of metals are a weight saving of 40–70%, and a reduction in engine acquisition cost of 10–40%. Other claimed benefits are reductions in structural and air borne noise of 5–20 dB, lower electromagnetic signature, and increased resistance to corrosion/erosion, wear and fatigue [26,132,134,138,139]. Despite these benefits, the present use of composites in engine components is virtually non-existent and is expected to remain so in the foreseeable future.

In the 1980s the US Navy installed about 100 composite ball valves in the Amphibious Cargo Ship, *USS Charleston*. These valves performed well and required virtually no maintenance for nearly 10 years, at which time the *USS Charleston* was decommissioned [26,138]. Nevertheless between 1991 and 1996 the US Navy spent nearly $US163 million maintaining and repairing bronze ship valves [140]. Commercial composite valves do not meet all the shock, flexure and fire requirements for general use on warships. The US Navy is designing its own composite ball valves that will meet the stringent naval performance requirements. Compared to conventional bronze ball valves, the composite valves are more corrosion-resistant, easier to maintain, 70–80% lighter and 50–75% cheaper to build [138]. Their prototype valves have composite components such as the valve housing, ball, ball seats and stem seals (see Fig. 10). Similar valves are expected to be used in the San Antonio class Amphibious Transport Dock (LPD-17) [138].

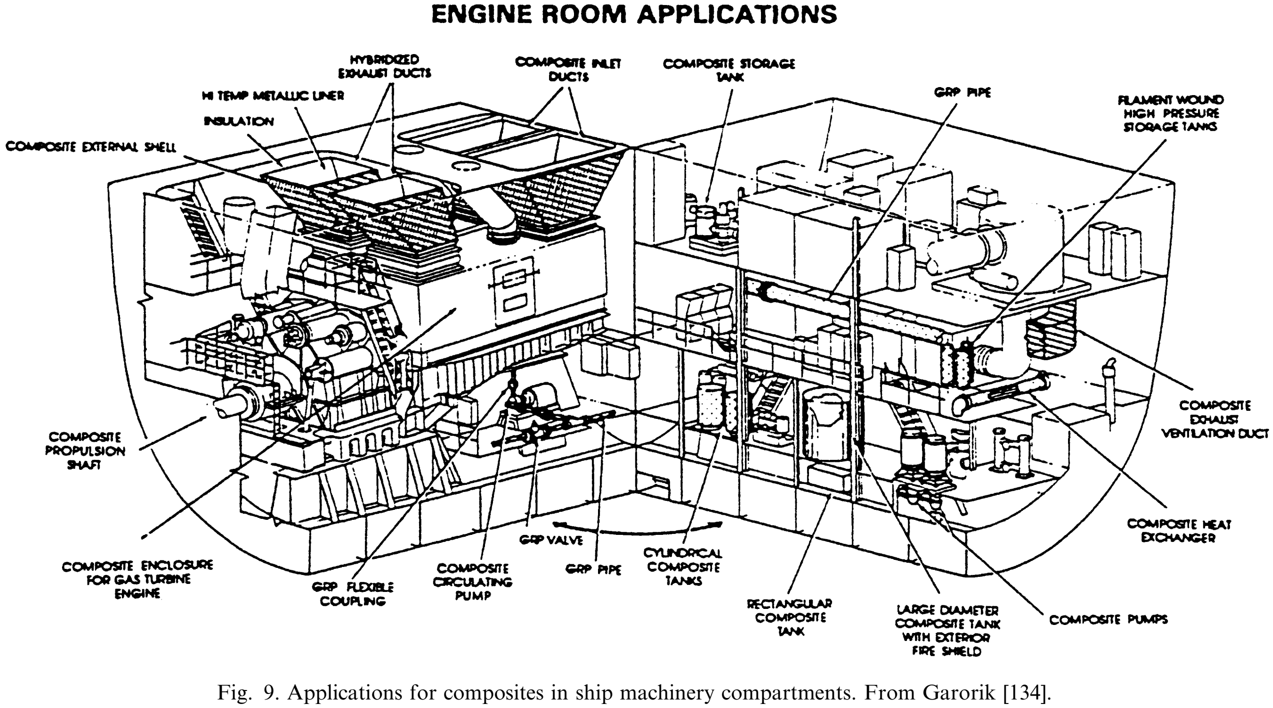

Fig. 9. Applications for composites in ship machinery compartments. From Garorik [134].

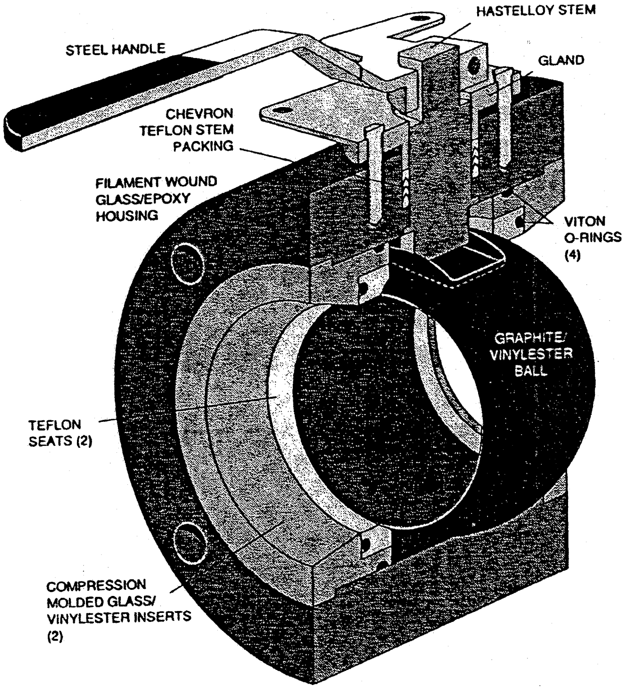

Fig. 10. Schematic of a composite ball valve for naval ships. From Bhasin et al. [140].

Also under development for the US Navy are composite pump bodies and impellers. Several years ago the navy had over 130,000 pumps on their ships. Many of the centrifugal pumps used for pumping seawater and brine are plagued by corrosion and erosion damage [141]. Composite centrifugal pumps are being developed to be lighter, more corrosion-resistant, less magnetic, non-sparking, quieter, and up to 30% cheaper than equivalent metal pumps. In addition, tests show that the hydraulic performance of composite pumps is superior to or at least similar to bronze pumps of the same size and capacity [138,141]. The components of pumps that may be made of composite include the casing, backplate, impeller, shaft sleeve, wear rings and throttle bushing. The US Navy has successfully trialed composite pumps on three Spruance class (DD-963) destroyers, and is considering using some composite pumps on the Arleigh Burke class (DDG-51) destroyers and a Nimitz class aircraft carrier (CVN-76).

6.7. Engine and equipment foundations

A large naval ship typically has over 1500 steel foundations for supporting machinery and equipment that have a total weight of 700–800 tonnes [130]. Several agencies have carried out feasibility studies to demonstrate the adequacy and performance of composite foundations for weight reduction. Kelly and Rockwell [130] report that one foundation made of glass-reinforced polyester composite measuring 1.2 m × 0.97 m was 58% lighter than a steel foundation of the same size. In another demonstration, a one-half scale model fresh-water pump foundation made of composite was 40% lighter and 50% cheaper to fabricate than a similar foundation made of steel [135]. Despite its lighter weight, the foundation provides adequate protection to machinery and equipment against underwater shock loading, and is impact damage resistant. The foundation also may reduce the acoustic and magnetic signatures of ships because of the vibration damping and non-magnetic properties of composites [94,132,134,135,138].

6.8. Heat exchangers

Heat exchangers on naval ships can experience severe seawater corrosion/erosion damage that results in costly maintenance and reduced ship availability. The US Navy is evaluating the use of carbon fibre composites in their heat exchangers [26,132,134].

6.9. Piping

One of the earliest uses of composites in naval ships was in pipes. The US Navy installed composite pipes on a destroyer escort in 1951 expecting them to be cheaper, lighter and more corrosion resistant than conventional brass pipes. However, these composite pipes were not successful because they rapidly degraded and leaked when transporting hot water [3,4,11]. Improvements to the quality and durability of composites led the Royal Navy to install composite pipes to the ballast system of their assault ships in the 1960s. Similarly the US Navy fitted composite pipes to their patrol frigates in the early 1970s [16,142]. There are estimates that the cost of fabricating and installing composite pipes on a ship will be 15–50% lower than for brass or stainless steel pipes [143,144]. Very few composite pipes are used on modern warships despite the probable cost saving. Nevertheless, the US Navy and Royal Navy continue to assess the potential uses of composite pipes [134,138,145].

6.10. Ventilation ducts

The US Navy is assessing the use of composite ventilation ducts on large warships to eliminate corrosion, reduce weight, achieve greater thermal insulation, reduce noise and lower life-cycle costs [132,134]. Composite ducting may be retrofitted to the Oliver Hazard Perry class (FFG-7) frigates, Arleigh Burke class (DDG-51) destroyers, the Ticonderoga class (CG-47) cruisers, the Enterprise class (CVN65) aircraft carrier plus a number of other ships. The US Navy also intends to test composite air grates on the Nimitz class (CV) aircraft carriers.

6.11. Deck gratings

The US Navy is evaluating the use of composites for deck gratings. They have fitted four aircraft carriers, including *USS Nimitz* and *USS Carl Vinson*, with composite deck gratings for this evaluation. Projections are that the study will confirm that composite deck gratings will provide a significant cost saving compared with conventional steel gratings over the life of a warship by eliminating corrosion.

7. Composite submarine structures

7.1. Background

Several navies have used composites with outstanding success in a diverse range of submarine structures for nearly 50 years. The first application was in submarine fairwaters, which are streamlined structures used to cover openings through the main steel pressure hull or cover protruding objects to provide favourable hydrodynamic flow. The US Navy first fitted an all-GRP fairwater to the conning tower of a Guppy class submarine in 1953 to determine if it would perform better than the conventional fairwater made of aluminium alloy. Such aluminium parts suffer severe corrosion and required on-going maintenance and repairs. The composite fairwater proved to be much more durable and required virtually no maintenance. Consequently, more than 25 Guppy class submarines were fitted with composite fairwaters during the 1950s and early 1960s [6–8,11,13].

During the same years the US Navy, Royal Navy and French Navy fitted a number of other composite structures external to the pressure hull of their submarines. These applications included sails [133], fins [16], mast strouds [16], casings over the upper pressure hull [11,18] and bow sonar domes [11,15–18]. In addition these navies undertook feasibility studies during the 1960s to assess the use of composites for submarine rudders and masts [11,13].

7.2. Composite pressure hulls and control surfaces

In 1966 Alfers [6] reported on the feasibility of building submarine pressure hulls with filament-wound composites. Although progress towards an all-composite naval submarine hull has been slow, a number of all-composite small submersibles and remotely operated underwater vehicles are in existence [146]. Several recent studies indicate that the use composites in pressure hulls should provide many benefits over steel. These studies identified as benefits reduced weight, better corrosion resistance, improved hydrostatic strength, and reduced electrical and magnetic signatures [133,147–150]. In addition, tests performed on 1/22-scale pressure hulls fabricated with composite showed the potential for operating depths 3–4 times that of steel hulls [138]. However, using composites in pressure hulls poses serious problems, such as extremely high construction costs, low interlaminar shear strength, susceptibility to compressive fatigue failure and poor fire-resistant properties [130,148,151]. For such deficiencies it is unlikely that composites will ever be used in large submarine hulls.

The Defence Evaluation and Research Agency (UK) has investigated the feasibility of lining the outside wall of the steel pressure hull with a sandwich composite material [149,150]. Covering the steel hull with composite cladding is expected to increase the overall buckling strength, lower fatigue strains, reduce corrosion and lower the acoustic, magnetic and electric signatures. Furthermore, some payload items and sensors might be embedded in the composite. Smith et al. [149,150] have performed preliminary feasibility studies of this design concept. However much more development work is required before the technology can be tested on a submarine. Composites are also being used in external hull structures on small submersibles. For example, a new submarine that is only 20 m long and about 2.5 wide is being constructed for the US Navy to undertake covert operations. The submarines are built with a steel pressure hull that is enclosed by an external structure that includes the nose fairings and tail which are made of composite materials [152].

Several groups are looking into the use of composites in submarine control surfaces such as the bow planes, fins and rudders [130,133,138,139,150,153,154]. Expected major benefits of using composites are to be reduced weight, construction costs and corrosion. Costs are reduced because the control surfaces can be moulded to the required hydrodynamic shape without machining, and because of the excellent corrosion resistance of composites. Koudela et al. [139] made a small fin from a hybrid composite containing carbon and glass reinforcement. This fin was nearly 50% lighter, 23% cheaper and had equal or superior hydrodynamic and acoustic performance to an aluminium fin of the same size. However, there are few applications of composite control surfaces on large submarines. Graphite-epoxy diving planes were fitted to a nuclear research submarine several years ago, although little information has been published on their performance. The Defence Evaluation and Research Agency is investigating the feasibility of fabricating submarine bridge fins and rudders using a FRP/anechoic-rubber sandwich composite to provide good acoustic stealth properties and shock resistance [149,152].

7.3. Masts

Composites are being used increasingly in submarine masts for communications, optronic and electronic surveillance as well as in non-hull penetrating masts [155,156]. Masts made of composites have a number of advantages over those made of steel, including lighter-weight and no corrosion. Composites allow moulding into complex shapes without the need for machining, and the incorporation of radar absorbing materials over the entire length of the mast [156]. The Royal Navy has fitted composite communications masts to the Upholder class submarines. A similar fitting occurs on the Royal Australian Navy's Collins class submarines. Some Type 209 submarines may be fitted with such a mast.

7.4. Internal structures, equipment and fittings

A wide range of composite applications within the submarine pressure hull is under consideration. Similar to surface ships, the applications include the bulkheads, decks, hatches, main propulsion shaft, ballast tanks, storage tanks, machinery, pumps, valves, pipes and ducting [8,95,138,141,147,148]. Estimated weight savings by using composites in such applications are about 400 tonnes for a modern nuclear submarine [133].

Development and testing work for these applications is usually not published in the open literature. A general opinion is that the US Navy has evaluated the main propulsion shaft, various machinery foundations and some air flasks made of composite on their research and development submarine, *USS Memphsis* [95]. These applications were tested first because they are relatively low risk and provide significant pay-off in terms of weight savings if they work. Evans et al. [147] suggest that once a satisfactory level of acceptance and confidence is attained for composites, then other internal applications having higher risk and higher pay-off will be tested, such as bulkheads, pumps and valves. However, the widespread use of composites on submarines is unlikely in the foreseeable future, and probably will not occur until these materials have gained broad acceptance on naval ships.

8. Summary and concluding remarks

This review of the diverse range of new applications for composites in warships and submarines is summarised in Fig. 11. In the figure the present stage of development for the applications is categorised into concept (C), technology demonstrator (TD) or completely developed (D). Most of the applications are at the concept or technology demonstrator stages, particularly for submarines. Most of the completely developed applications are found only on relatively small naval ships (e.g. patrol boats, MCMV, corvettes), or non-structural non-critical components on large ships and submarines.

The replacement of naval structures, components and machinery made with steel, aluminium alloy or bronze with composites has in most cases been a difficult and slow process. Metals perform extremely well in most applications. Designers, builders and operators of naval vessels have a great deal of confidence and experience with metals. Thus only applications where composites have the strong potential to reduce acquisition and through-life maintenance costs, and improve ship stability and performance are they likely to be used instead of metal.

The other factors impeding the more widespread use of composites are complex. One important factor is the lack of design rules, empirical data and simple-to-use models for optimising the design of large, complex load-bearing naval structures. Despite the use of composites in naval craft for 50 years, the information and tools needed by naval architects is not complete. For example, simple analysis tools for determining failure modes of complex naval composite structures, particularly under blast, shock, collision and fire events, are virtually non-existent. Furthermore, the scaling laws for composites are complex due to their anisotropic properties, which makes the design of load-bearing structures more difficult than designing with metals. To overcome the lack of information, it is common practice to design composite ship structures with safety factors that are far higher than when designing for metals [147]. Most composite structures are designed with safety factors between 4 and 6, although values up to 10 are applied when the structure must carry impact loads [157]. The high safety factors result in structures that are heavy and bulky, and this seriously erodes the strength-to-weight advantage offered by composites.

Another important issue is the preconceived notion as to how a composite structure should be designed based on experience gained from metal structures. Some naval architects apply the same rules and techniques used for designing metal structures to composite structures. This often results in the composite structure having inferior performance. For example, composite ship joints often have similar design features to welded steel joints despite the difficulty in joining composites, and as a consequence GRP joints can have lower strength and fatigue resistance [26,158].

A perceived lack of high-quality, low-cost production methods has been another factor limiting the use of composites in large naval vessels. Construction cost is a primary driver of any marine design, and for many years composites were not cost competitive with conventional materials (except wood) in most shipbuilding applications [131]. Furthermore, until recently most composite naval structures were fabricated by wet lay-up, which can be a slow, labour-intensive and expensive process.

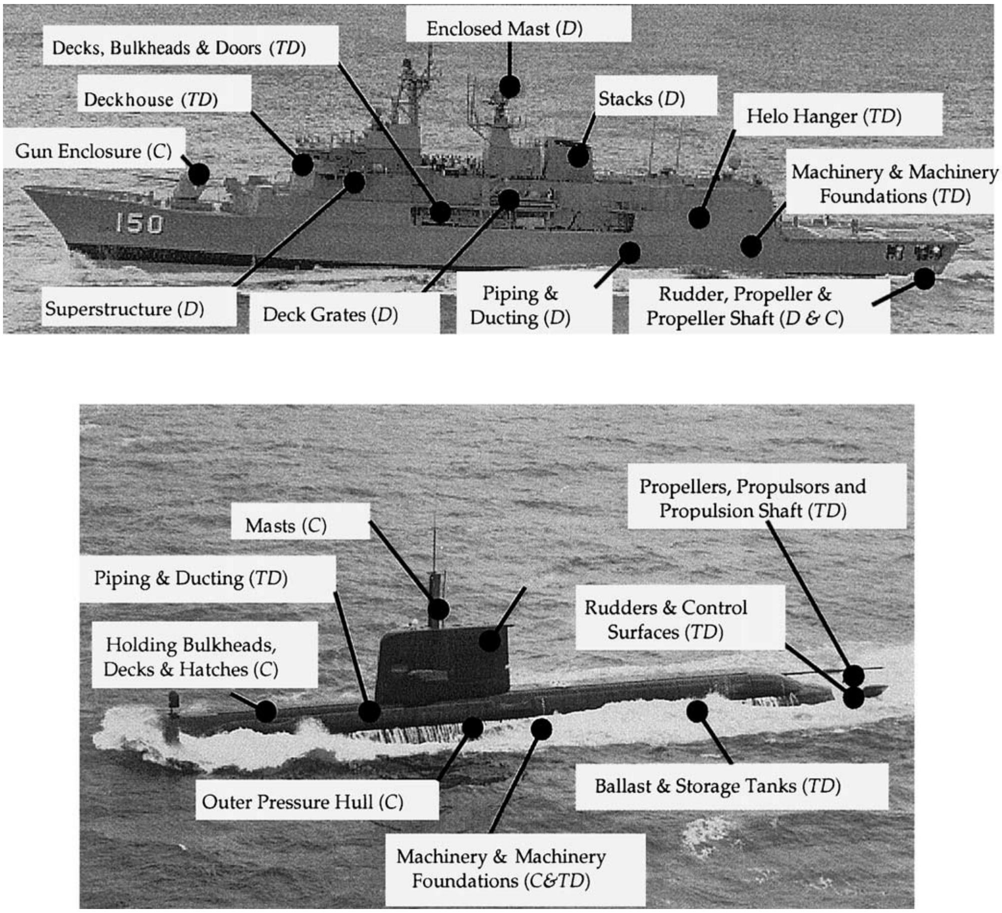

Fig. 11. Applications of composite structures to naval ships and submarines. The letters C, TD and D mean that the application is currently a concept, technology demonstrator, or developed and in-service, respectively.

Another drawback is the poor quality control with the wet lay-up process. A fact that requires composite structures to be designed with partial safety factors of 2 to account for fabrication defects as against steel with a safety factor of 1.5 whose manufacture is well controlled. Control problems can be overcome by low-cost fabrication processes, such as SCRIMP and resin transfer moulding, that produce high-quality composites [62,137,159,160]. However, these processes require shipbuilders to introduce new production methods, which can be prohibitively expensive.

Shipbuilders also lack models or a large database of consistent information for estimating the cost of fabricating naval structures with composites. In this paper numerous examples are given where the cost of building with composites is difficult to estimate. Cost is dependent on a variety of factors, such as type of composite, fabrication process and the incorporation of electromagnetic shielding and radar absorbing materials. For example, the construction cost of a frigate superstructure built of composite may be 10–240% more expensive than for steel. Only recently have many ship designers and operators become aware of the reduced maintenance and fuel consumption costs when using composites. Through-life cost savings that will far out-weigh any increase in acquisition cost.

Stringent performance requirements have hindered the use of composite in naval vessels. Composite structures are required to pass a series of strict regulations relating to air-blast and underwater shock damage resistance, fire performance (flammability, fire, smoke, toxicity, structural integrity), fragment/ballistic protection, and radar/sonar capabilities. The data needed to assess the survivability of composite structures are extremely limited, and conducting tests to determine their performance under blast, shock, ballistic and fire conditions is time-consuming and expensive. Meeting the requirements is a major problem with topside structures, where for example considerable effort has been devoted to designing joints capable of withstanding air blast loading.

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