Hull Construction with Composite Materials for Ships over 100 m in length

by

Konstantinos Galanis

B.S., Marine Engineering – Hellenic Naval Academy

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

NAVAL ENGINEER
and
MASTER OF SCIENCE IN OCEAN SYSTEMS MANAGEMENT
At the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2002

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
AUG 2 1 2002
LIBRARIES

© 2002 Massachusettes Institute of Technology. All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part.

Signature of Author.............................. ......
Department of Ocean Engineering
10 May 2002

Certified by:...
David Burke
Senior Lecturer, Department of Ocean Engineering
Thesis Supervisor

Certified by:...
Henry S. Marcus
Professor of Ocean Engineering
Thesis Supervisor

Accepted by:....................... ....
Professor Henrik Schmidt
Professor of Ocean Engineering
Chairman, Department Committee on Graduate Studies

BARKER

Αφιερώνεται στην
Αγία Παρασκευή

Acknowledgments

There were and are numerous persons who supported my efforts in order to achieve this accomplishment prior to my acceptance and during my graduate studies at the Department of Ocean Engineering of Massachusetts Institute of Technology. First of all I have to express my deepest acknowledgments to the Hellenic Navy (HN) for selecting me among other capable officers and also thank the Greek taxpayers for investing their money on me, via the HN.

This study was supervised and directed from my thesis advisors, Dr. David V. Burke (the technical part) and Professor Henry S. Marcus (the economic part). Dr. Burke showed a superior level of support, guidance and understanding towards my efforts and ideas. Without his advice this thesis would not be as complete as I hope is. Pr. Marcus and his wide knowledge of the shipbuilding industry helped me understand past, existing and innovative issues concerning theory and applications of managing shipping companies.

Taking this opportunity, I would like to thank all my teachers and professors, who helped and educated me from my early stages of school until now, and whom I hope to satisfy with this product. Special thanks are paid to my professors from the Hellenic Naval Academy, Pr. Katsamanis, Pr. Boufounos, Pr. Konstantopoulos, Pr. Chatzilaou and Pr. Kiritsi-Giallourou for their support and comments. Additionally, I would like to thank Pr. Patrikalakis and Captain (USN) McCord for their support concerning my studies and administrative issues while being at MIT.

Ειδική Μνεία

Είναι τιμή μου και περηφάνεια μου να αφιερώσω όλη μου την ακαδημαική και στρατιωτική καριέρα στην μητέρα μου Χριστίνα, τον πατέρα μου Παναγιώτη και την αδερφή μου Κατερίνα. Είναι πάντα στο πλευρό μου και εύχομαι ο Θεός να τους έχει καλά, ούτως ώστε να μπορέσω να τους αφιερώσω περισσότερες χαρές στο μέλλον. Είστε πάντα στην καρδιά και το μυαλό μου.

Επίσης, συμπαραστάτης σε αυτήν μου την προσπάθεια ήταν ο σύζυγος της αδερφής μου Αντώνης. Κουράγιο πάντα μου έδιναν με τις φωνούλες τους, η ανιψιά μου Χριστίνα, το λατρευτό μου βαφτιστήρι Γωγουλίνι και το βαφτιστήρι μου Κάρολος. Εύχομαι επίσης οι Παπούδες μου, παρότι δεν βρίσκονται πιά στην ζωή να μπορούν να μοιραστούν μαζί μου όλη την χαρά που με περιβάλλει.

Αυτό το όνειρο δεν θα λάμβανε ποτέ σάρκα και οστά, χωρίς την απεριόριστη συμπαράσταση και υποστήριξη της γυναίκας μου Χαράς. Δεν υπάρχουν λόγια να περιγράψω αυτά που νιώθω για εκείνη. Επίσης, κατά την διάρκεια των σπουδών μου έλαβα αμέριστη συμπαράσταση και κατανόηση από την αγαπημένη μου Λάουρα. Σε ευχαριστώ. Αξίζει να σημειωθεί ότι στις δύσκολες στιγμές μου είχα να αντιμετωπίσω, δεν θα τα κατάφερνα χωρίς την απόλυτη στήριξη του φίλου μου Δημήτρη Αιβάτογλου.

Τέλος, θα ήθελα να ευχαριστήσω τους φίλους μου Σπύρο, Σοφία, μικρό Γιάννη, Γιώργο Κοκκάλα, Γιώργο Κωνσταντινίδη, Κώστα Ψαλλίδα, Περικλή, Ιουλία, Θοδωρή Καρύδη, Πάρη και Μάνο Χανιωτάκη. Εσύ Γωγώ εκεί ψηλά, απλά σου είμαι ευγνώμων.

Hull Construction with Composite Materials for Ships over 100 m in length

by

Konstantinos Galanis

Submitted to the Department of Ocean Engineering on May 10, 2002 in Partial Fulfillment of the Requirements for the Degrees of Naval Engineering and Master of Science in Ocean Systems Management

ABSTRACT

The operational envelope of the maritime industry requires high performance marine vessels, which demand increased structural integrity and durability, coupled with significant weight reduction and minimization of cost. The design and fabrication of a "large vessel" by use of composite materials is within the current technology. However, a number of major technical and economic aspects are questionable. This study will examine the structural design for vessels longer than 100m. It will also identify the major advantages and disadvantages of this composite structure compared with one made of steel, focusing on the technical and economic aspects.

Material selection, fabrication methods and design concepts for composite structures, such as elimination of frames, will be explored and comparisons will be developed. The potential to significantly reduce or even eliminate the risk areas will be evaluated. Four different structural designs of a hull from composite materials are examined for a midship section of an existing naval ship (DDG51 type) and they are compared to the one built from steel. In order to select the best option of these structural designs, three variants are analyzed: structural configuration of composites, material option and fabrication process. Additionally, the effect of several critical areas, such as safety factors selection, present and future structural limitations, required fabrication experience, durability, complexity, infrastructure issues, and a cost and market analysis of using fiber reinforced plastic (FRP) in ship design and construction are included in this study. The proposed hull design combined with the optimum materials and fabrication method shows that a large ship is both technically and economically feasible.

Thesis Supervisors: David Burke, Senior Lecturer, Department of Ocean Engineering

Henry Marcus, Professor of Ocean Engineering

Table of Contents

List of Figures

List of Tables

1 Introduction

The structural designer is faced with the challenge to continuously strive for lighter and more efficient structures, while facing increased safety requirements and regulations. The weight saving potential through the use of sandwich structures is impressive in most applications and has been under examination for several decades. A very rough estimate of the weighting factors of different structures is presented in Fig. 1 and is based on the view of experts that in marine structures the following observations can be made [Ref 86]:

- aluminum structures are about 50% lighter than the typical steel ones
- glass fiber reinforced plastic (FRP) sandwich is 30-50% lighter than aluminum
- carbon FRP sandwich is 30% lighter than glass FRP sandwich

The figure is a rough representation and the actual value depends additionally on the sophistication of the alternatives compared.

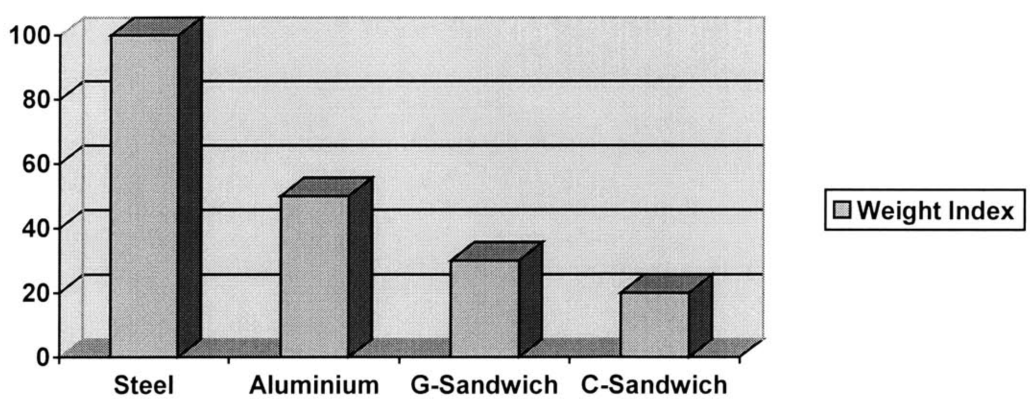


Figure 1. Weight saving potential with different materials. [Ref 86]

In spite of this substantial weight saving potential there are several other considerations that the structural designer has to take into account, before making a decision. Constraining issues are manufacturing possibilities, joining techniques, local strength, damage tolerance, cost and serviceability especially in cold conditions.

Steel became the marine construction material of choice in the late 1800's due to its stiffness, strength and damage tolerance. Composites became common marine construction materials in the 1960's. Composite structures are being used increasingly in many areas of ship construction. Whether for structural or non-structural applications, the aim is always to improve performance and to prepare ships for the challenges of the future. FRP has the advantages of light weight, corrosion resistance, ease of construction, and lower cost in comparison to steel, wood and aluminum in "small" vessel applications (length less than 100m). [Ref 56] Sandwich composites take some of the FRP advantages one step further by using relatively thin FRP skins (inner and outer layers) "sandwiching" a low-density foam or balsa core to achieve adequate panel stiffness at even further reduced weights.

While advanced composite materials have been widely accepted for use in aircraft structures for many years [Ref 18], the use of composites in marine structures has only recently come under consideration for possible replacement of metals. With the desire to improve performance of large surface ships and submarines [Ref 69], it has become necessary to reduce the structural weight of these vessels. This reduction in weight can be achieved with the substitution of advanced composite materials for metals used in certain applications because the specific strength and stiffness of advanced composites, such as graphite fiber reinforced epoxy, are much higher than that of conventional metals. Some additional benefits of composites are improved damping and the fact that they are nonmagnetic, and their manufacturing processes can be automated.

Composites are presently used for sections of large steel vessels, including non-pressure hull decking, nose sections, sails and diving planes for submarines, weapons enclosures and masts for destroyers, funnels on cruise ships and hatch cover for barges. Three-dimensional (3-D) through-the-thickness braided composites offer several advantages over conventional materials as well as traditional laminated composites when applied to marine structures. These are high interlaminar shear strength and fatigue resistance. [Ref 62] Some specific applications that can benefit from the properties of 3-D braid are propellers and control surfaces.

Although shipbuilding is classified as heavy industry, with consequent impressions of large steel structures and heavy machinery, composites are finding increasing use in ship construction. On vessels of all sizes they are used for preservation of structure, the supply and maintenance of essential services, and in the manufacture of outfit items. Besides forming a fundamental constituent of the main structure of any smaller vessels, composites are also found in the minor structure of larger vessels. However, in many cases the quantities used in any one vessel are relatively small in terms of the composite manufacturing industry, so shipyards tend to use existing technology and products rather than develop products for specific uses. A problem faced by both shipbuilder and shipowner alike is that most materials used in ship construction tend to degrade in a marine environment. [Ref 4]

1.1 Scope of thesis

The importance and the potential innovation that composite materials represent in nautical, naval and military construction in Europe and in most of the countries of the world involved in these kinds of construction have inspired the author of this thesis. The construction of large vessels from composite materials represents a challenging task. Although there has been a decrease in the activity of the nautical construction industry, innovation and creativity can lead to the development of new markets. The use of composite materials can contribute to this.

The aim of this thesis is to perform a structural and optimization analysis of selected configurations of a hull, in order to examine the feasibility of constructing hulls with composite materials for "large" vessels (over 100m in length). The design and fabrication of a large vessel from composite materials is shown to be totally within the present state-of-the-art, but a number of major technical and economic aspects are questionable. The advantages and disadvantages of using composite materials in ship construction are presented. Also, reduction of the perceived risk in using current technologies in large-scale ship fabrication had to be included.

Figure 2 presents a general systems engineering approach applied to ship design. Considering the vessel as a subsystem, two are the major dependences to the system (ship design and construction) that are under examination in this study: the economics related with the construction and operation of a vessel and the fabrication requirements for this application.

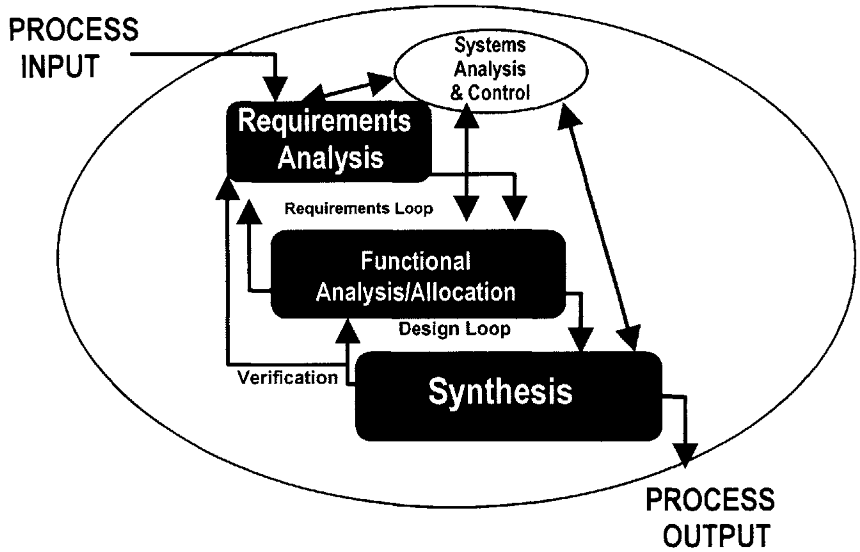


Figure 2. Systems Engineering Process

When the vessel represents the system, material selection, structural configuration, joining, fatigue and fracture, and fire performance synthesize the major critical areas that have to be investigated and evaluated, due to the fact that they consist the major hurdles of constructing large vessels. This thesis emphasizes the first two areas mentioned above.

Moreover, the present study addresses all the crucial areas of constructing large vessels with composite materials and defines the present and future limitations. Additionally, the appropriate design criteria will be discussed and the associated complexity of this process will be stated, while several alternative options will be presented. Taguchi methods will be the optimization method for the selection of the composite materials for the hull. [Ref 30] A statistical commercial software, JMP, enhanced the capability of exploring the best approach to the solution and the definition of the boundaries of the design space.

Four different structural designs of a hull from composite materials are examined for a midship section of an existing naval ship (DDG51 type) and they are compared to the one built from steel. The best of these hull designs, embeds all the current state-of-the-art technological steps of the marine composites applications. A commercial finite element code MAESTRO, will be the tool for the evaluation of this design for a specific set of selected loads. Furthermore, a methodology to design composite primary hull structures is proposed.

This study will try to examine in depth areas that play a critical role in ship design and construction and consist presently the areas of uncertainty and lack of confidence in using composite materials for the construction of large vessels. These areas are the following: safety factor selection, installation of systems, required experience, durability, complexity, the appropriate infrastructure and the health/environmental issues. Finally, the major assumptions will be discussed and the inherent risk will be examined. There are numerous questions raised, which will not be satisfactorily answered due to the limited and selected area of examination for this feasibility study. There are several studies that have to be considered before greater confidence in the feasibility of a large vessel built from composite materials can be achieved.

A cost analysis of using FRP in ship construction is presented and the potential benefits are examined. In order to include additional cost and risk factors related to the ship construction, an evaluation of several fabrication processes and their applicability to ship construction has to be examined. Productivity and producibility issues play significant role to ship construction and can affect ship constructions costs. Therefore, a feasibility assessment of the existing fabrication systems for the construction of large marine composite structures is included.

1.2 Overview of thesis

The operational requirements of the maritime agencies and organizations require high performance marine vessels, which demand increased structural integrity and durability coupled with significant weight reductions, while requiring increased cost reductions. A superior performance of large composite marine vessels can come at affordable costs compared to metallic alternatives. Chapter 2 describes the background of the marine applications of the composite materials, while presenting the candidate fabrication methods for the construction of large vessels with composite materials. Additionally, the Visby class vessel, the biggest existing vessel constructed from composites, is reviewed.

Chapter 3 describes the types of composite materials applicable to marine structures and presents the methodology developed for the selection of the fibers and resins. The properties and the characteristics of the marine composites are also described. Chapter 4 includes the structural analysis of the four different hull designs and analyzes the structural optimization performed. Chapter 5 is related to the economical aspects that are in direct and indirect relationship with this special type of construction. Chapter 6 describes an overall application at a trimaran design, including both structural and economical analysis. Finally, the last chapter presents the conclusions and the recommendations for future research.

2 Background

The applications for composite materials is extensive, covering all types of end-uses, markets, and applications: military, defense, aerospace, automotive, sporting goods equipment, medical applications, electronics, conductivity, utility poles, household appliances, storage tanks, beams, drive shafts, engine components, bearings, seals, furniture, etc. The list is endless. Most importantly, the composites are used to replace monolithic materials (especially metals), to save weight and energy, to reduce part count and assembly cost, and because of the versatility of the interaction between the design of the materials and the design of the component. [Ref 4] Naval architects are rapidly accepting the latest construction techniques using composites to benefit from the following advantages:

- Very low weight — - enables increased speed; - increases payload; - reduces fuel consumption
- Fire Performance — - excellent fire resistance; - interior panels prevent flame spread and smoke emission
- High stiffness — - reduces (or eliminates) supporting framework; - carries fittings readily
- Durability — - excellent fatigue, impact and environmental resistance; - fiber-reinforced plastics are non-corrosive
- Improved appearance — - panels can have smooth or textured finishes; - integral decorative facings can be incorporated
- Rapid fitting — - modular construction ensures panels are interchangeable; - large panels are easy to handle and install due to light weight
- Versatile — - wide range of design possibilities to suit circumstances

2.1 Marine Applications of Composite Materials

The use of polymeric composites in a marine environment is well established. Applications range from pleasure boats and military vessels to helicopter decks on offshore platforms, and one of the main reasons for using these materials is their good resistance to harsh environmental conditions. [Ref 34]

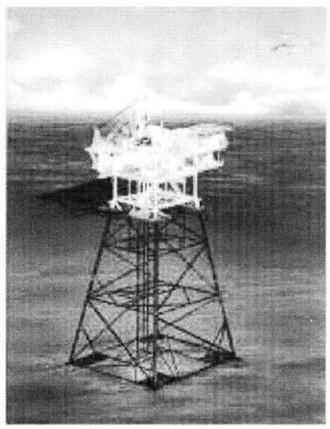


Figure 3. Offshore structure application (fire protection panels, water piping systems, walkways & flooring, tanks and vessels, cables housings, shelters, etc).

However, although much qualitative data and experience now exist, the transfer of this 'know how' into quantified design rules is proving to be a long process. The multiplicity of resins, fibers, test conditions and environments makes generalizations very hazardous and the time scales necessary to validate predictions for particular systems are too long for most research projects. If the safety factors associated with aging uncertainties are to be reduced it is essential that existing data be pooled so that design tools can be developed more rapidly. The use of composites in underwater applications is increasing, with recent examples in submarine structures, wellhead protection structures for the offshore industry and oceanographic equipment.

In reviewing technology advances through the centuries, it is evident that materials development plays a key role in significant technology breakthroughs. If one but reflects on certain historical eras, materials have been either identified with the period or have been critical to resulting developments within the period. Included are the stone age, iron age, industrial revolution, nuclear age, and electronic revolution. Today, with the increasing need for performance-oriented material and structural systems, the development and introduction of advanced composite materials represents a new evolution in materials technology. [Ref 48]

These new materials represent a marriage of diverse individual constituents, which, in combination, produce the potential for performance far exceeding that of the individual elements. This synergism makes composite materials both enabling and pervasive in government and commercial applications.

FRP materials offer tremendous potential for applications in a marine environment, where their corrosion resistance and light weight are their principal advantages compared to metallic structures. Many applications exist and overviews are available. Considerable efforts have been made over the last 25 years to improve the understanding of the durability of these materials but design safety factors remain high for loadings other than static (long term, cyclic, impact). There is also a widespread mistrust of polymeric composites for fire-sensitive areas, in spite of considerable experience on passenger ferries in Scandinavia and increasing use offshore.

The materials that are being considered for the majority of marine applications are not the high-performance carbon fiber composites, prepared by elevated temperature cure of prepeg layers, which have been adopted by the aerospace industry. Here, we are mainly concerned with glass fiber reinforced composites prepared by contact molding (hand lay-up). Typical fiber volume fractions are around 30-40%. There is also a little use of carbon fibers with epoxy resins and honeycomb core, confined to racing vessels and luxury boats where price is not an important parameter in design. For tubes and tanks filament winding or contact molding are the main fabrication methods.

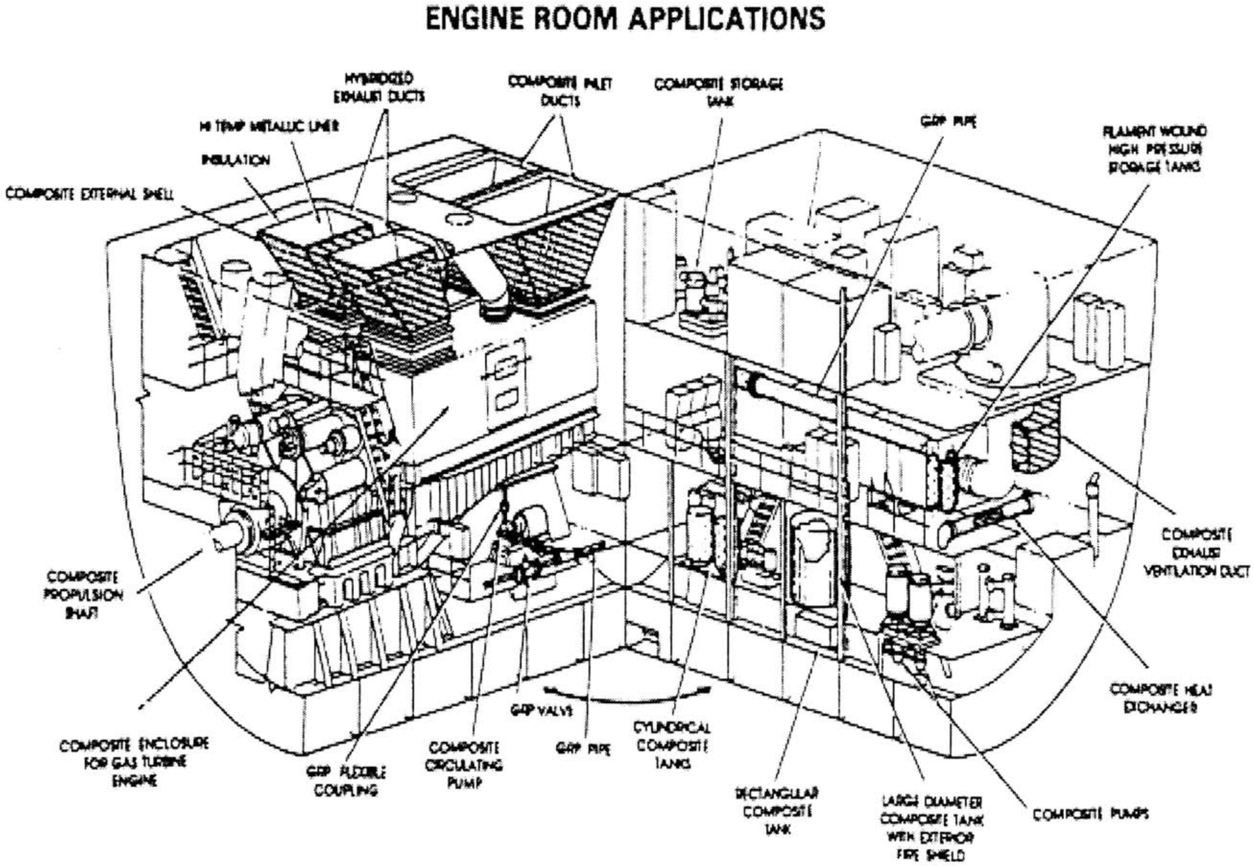


Figure 4. Applications for composites in ship machinery compartments. [Ref 76]

Typical resins are polyesters, epoxies, vinyl esters and phenolics. The reinforcements are generally woven fabrics, often coupled with chopped strand mat layers. The ply-based analysis using laminate theory is therefore of limited use as unidirectional ply data are not available. In addition to the monolithic composite structures there are also a large number of applications of sandwich structures. The most frequently used core materials are closed cell PVC foams and balsa. These typically have densities from 80 to 200 kg/m^3 but show poor fire resistance. Heavier mineral based cores may be the only solution when fire performance is critical.

2.1.1 Potential applications of marine composites

FRP composites potentially offer significant weight savings in surface warships and fast ferries and may be considered at a number of levels:

- Superstructures [Ref 50]
- Masts
- Secondary hull structures (internal decks and bulkheads, fairings)
- Primary hull structure

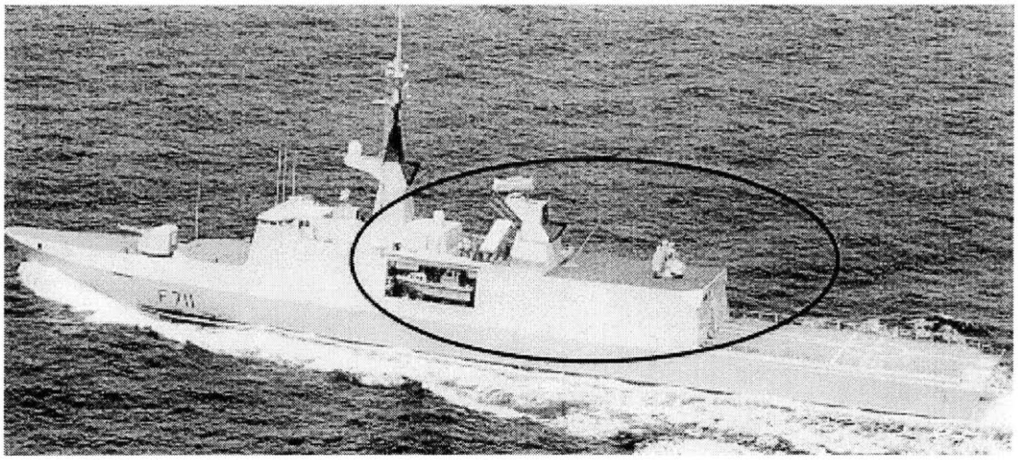


Figure 5. La Fayette frigate with the composite superstructure section. [Ref 76]

One concern regarding the use of composites for large ships hulls is a reduced overall hull girder stiffness and the implication for propulsion shafting alignment. Interestingly, a US Navy study concluded that a hull bending stiffness of 25% of the steel baseline vessel could be achieved, and loads induced in the shafting by the cantilevered propeller would still be an order of magnitude higher that those caused by hull bending. [Ref 70]

Although one of the often stated advantages of composites is the ability to form them into any shape, for large structures such as superstructures [Ref 101] it can be more cost-effective in terms of the tooling to design a structure which is fabricated from flat panels, since a flat panel tool can be re-used many times and its cost amortized over many projects. [Ref 66]

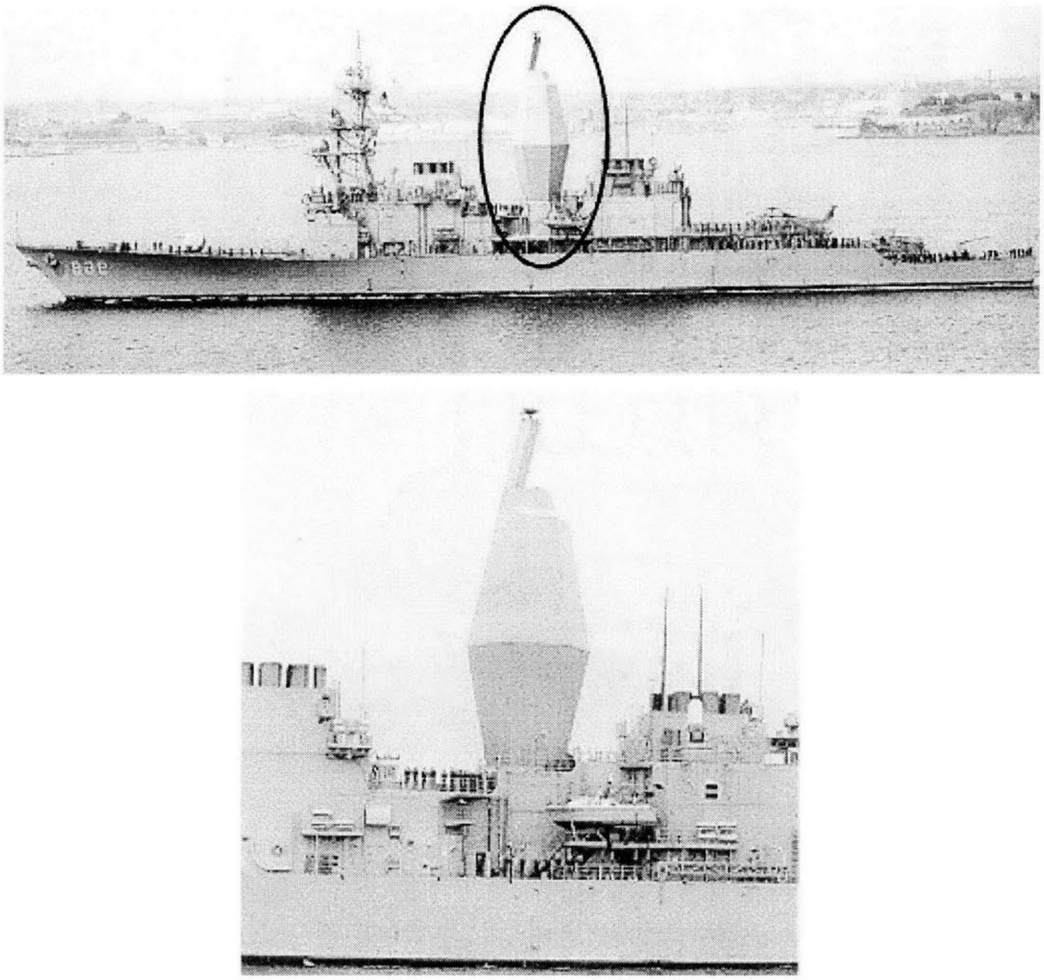


Figure 6. USS Arthur W. Radford showing the AEM/S system. [Ref 76]

There are great benefits to be realized from employing composite materials in marine structures. When correctly specified, these materials offer ship operators a range of advantages over traditional metal structures, such as weight saving, durability, corrosion and fatigue resistance, and fire performance. Advances in closed mold processing technology and in particular the introduction of vacuum methods are leading to cleaner production and higher quality moldings. However, there is still a need to develop improved techniques for efficient and reliable joining and the question of end-of-life must be addressed. [Ref 11]

Materials tend to be the main cost driver when comparing composites with mild steel. The low Young's Modulus of Simple E-glass composites can be accommodated in hulls up to 85 meters in length [Ref 76], so low cost hull mold concepts are now needed. Composites will continue to expand in use and be specified for smaller but complex shaped parts where steel and aluminum fabrication cost is high, such as bow fairings, rudders [Ref 67], funnels and even trimaran outriggers. The ability to design the material and combine structural reinforcements with other materials is giving rise to new and advanced concepts for improved stealth of warships' topsides structure.

FRP composites are now established as marine construction materials, their long term behavior are well understood and by following a logical approach to analysis, testing and trials as designs are developed, highly durable and cost-effective ship structures result.

2.2 Applications in shipbuilding industry

There is an increasing worldwide demand for small, low signature, long range/endurance, and low cost ships, for close in-shore operations. The optimum size of such a ship is still evolving but ships in the range of 300-foot long and 1200-ton displacement would appear to be representative of the class. [Ref 78] However, efforts to actually incorporate FRP into ship construction have been hampered by a perception of high risk in using a structural material without an established history and the fact that the use of metallic materials, specifically steel, has been very successful. [Ref 63, Ref 64]

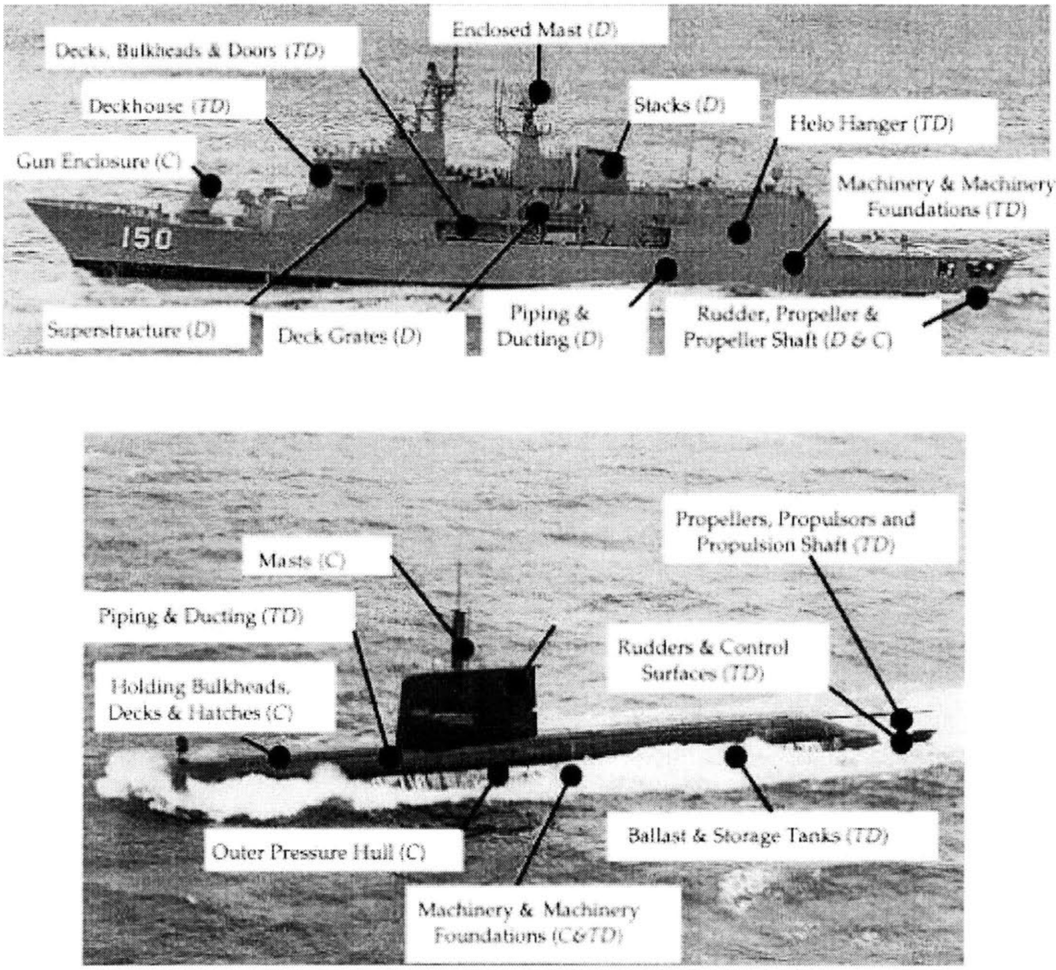


Figure 7. Applications of composite structures to naval ships and submarines: the letters C, TD and D mean that the application is currently a concept, technology demonstrator or developed and in-service, respectively. [Ref 76]

2.2.1 Pleasure boat industry

Small pleasure boats have been built from composites for over fifty years. The principal fabrication route is hand lay-up, using glass/polyester composites, although there is some interest in injection methods such as Resin Transfer Molding (RTM) for larger series. Competing materials are wood and aluminum but price and ease of maintenance have resulted in composites representing around 90% of the market. Especially, the small boat industry is dominated by fiberglass, since this material allows relatively fast, inexpensive mass production in comparison with the other materials. Large boats and ships are not mass-produced at sufficient levels to yield a significant construction advantage to fiberglass; thus there is more disparity in the choice of materials. A significant innovation in this area is the growing awareness of the benefits of quality control procedures. [Ref 3]

2.2.2 Passenger transport

There are an increasing number of fast passenger vessels under construction and the design of such vessels will be used to illustrate the origins of safety factors in design. Vessels transporting passengers in international waters are subjected to Safety of Life at Sea (SOLAS) regulations issued by the International Maritime Organization (IMO), which severely restrict the materials options. For large ships the hull and most bulkheads must be non-inflammable, thus excluding polymeric composites. For smaller boats and fishing vessels the rules are less strict. In Sweden and Norway sandwich construction is widely used for fast passenger transport. [Ref 75, Ref 60, Ref 53]

2.2.3 Recreational Applications

Composite material technology development in recreational boats has come the closest to matching the advances made for aircraft. Composite use has soared in the recreational marine industry due to different economic and operational factors than commercial and naval shipbuilding. Boat manufacturers began using composites in the 1950s with designs such as the 8.5 m Triton, the 12.2 m Block Island, and the 4.3 m Sunfish. These early designs were modifications to wood construction, providing cost advantages due to mass production and reduced maintenance over their service lives. From the experience gained, design and manufacturing techniques for lower performance craft was developed.

2.2.4 Commercial Applications

Cost is a major concern in commercial shipbuilding because of international competition. Commercial shipbuilding has virtually ceased in the U.S. because U. S. ship construction has historically been more costly than foreign ship construction. Composites have only been used in the U.S. when economically viable or required for performance. Composite usage has extended to fishing trawlers, lifeboats, passenger ferries, and larger ships such as cargo ships and tankers. Industrial submersibles for research and inspection have also used composites to help them achieve their requirements. [Ref 102]

2.2.5 Military Applications

The most significant naval application of fiber-reinforced plastics has been in construction of mine countermeasure vessels (MCMV). [Ref 58] The first GRP hull was first conceived by the U. S. Navy in 1946 with contracts for two 8.5 m personnel boats. GRP use then spread to utility and patrol boats. There are only limited applications on larger surface ships and submarines, but many feasibility and engineering studies are being conducted. [Ref 94] Growth of composite uses on naval vessels has been hindered by stringent performance requirements and the need to keep cost to a minimum. Specific requirements include noise, shock, ballistic protection, radar/sonar capabilities, and fire performance. [Ref 61]

2.3 Fabrication Methods

Four different fabrication methods are efficient for the construction of large parts for ships: ultra-violet-cured vacuum-assisted resin transfer molding (UV-VARTM), ultra-violet-cured pre-preg (UV-PPG), low-temperature-cured pre-preg (LTC-PPG), or vacuum-assisted resin transfer molding (VARTM). [Ref 78]

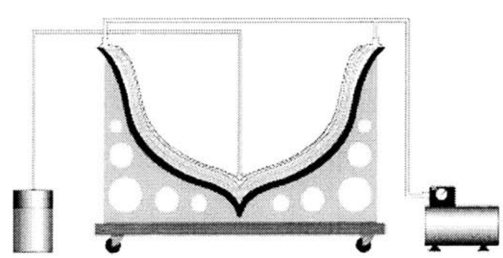


Figure 8. Graphical representation of vacuum-assisted resin transfer molding (VARTM) method.

On the technology front, processes that use thermoset resins, such as fiber placement, resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM), have become accepted if not preferred manufacturing techniques for the fabrication of composite structures in the Aerospace/Defense sector. [Ref 77]

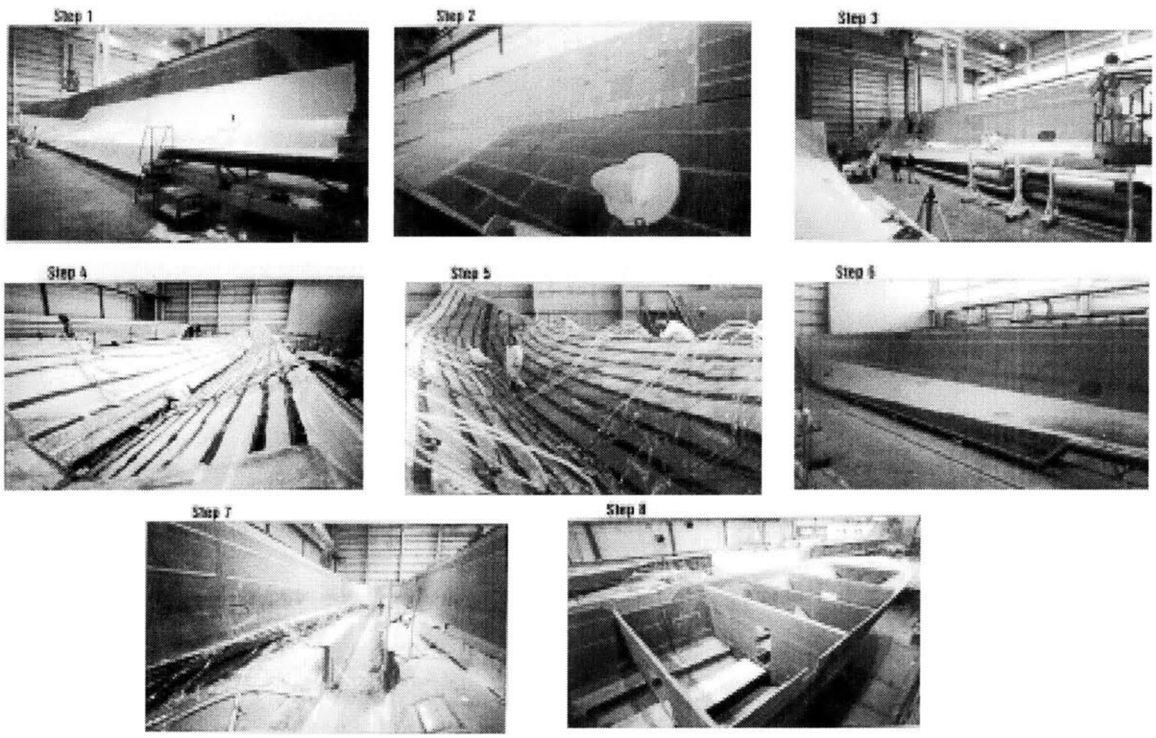


Figure 9. Step by step manufacturing using the VARTM method.[1]

One example of the basic steps in the VARTM method presented in Figure 9 are:

1. Operators place three layers of dry knitted E-glass fabric in the mold over the cured skin coat, to form the inner skin of the laminate sandwich.

---

[1] Inside Manufacturing: Megayacht builder refines vacuum infusion process, Composites Technology, November/December 2001

2. Grooved foam core is laid over the inner skin. Pink panels feature IMS-cut 1/8-inch grooves. Darker panels are of the more flexible double-cut variety.

3. Three additional plies of 32-oz. biaxial 0/90 E-glass fabric, laid over the foam core, complete the dry laminate sandwich.

4. With the mold laid over its side to reduce resin travel distance, resin feeder lines and bag are positioned over the laminate and a vacuum is pulled.

5. Vacuum is increased and resin is drawn through white feeder lines that pass over the mold side to unseen resin barrels positioned around mold. Operator (center) observes infusion through the clear bag.

6. After the laminate cures, bag and feeder lines are removed and mold is returned to upright position, to facilitate joining the hull halves.

7. A resin-and-fabric patch is applied inside the hull, along the centerline joint, and four longitudinal girders are infused in place, using grooved foam core, E-glass and carbon fibers in the laminate.

8. Bulkhead panels, infusion molded outside hull and laminated into place, provide transverse stiffness needed before hull demolding.

2.4 The VISBY class[2]

The design of Visby class is completely based on the use of composite materials. [Ref 98] Kockums AB/Karlskronavarvet (KAB) has a long tradition in the building of naval ships both in

[2] Kockums AB/Karlskronavarvet (KAB) is one of the major producers of large composite structures for the Swedish Defense Forces and has been working with composites for more than 30 years.

metallic materials such as steel and aluminum, and also in composite materials, preferably in FRP-Sandwich. [Ref 13]

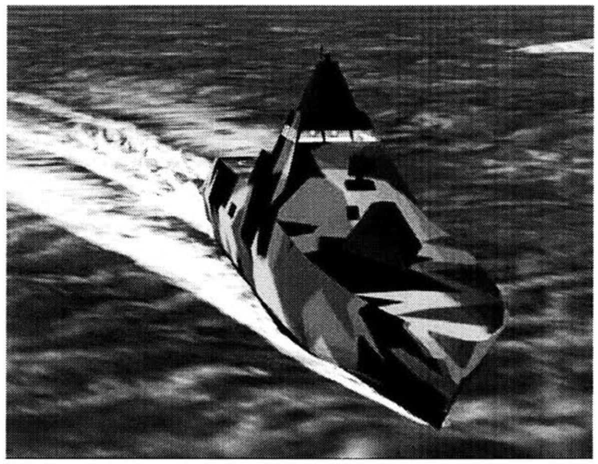


Figure 10: Visby Class corvette. [Ref 12]

The Visby is designed to minimize all signatures – optical and infrared signature, above water acoustic and hydroacoustic signature, underwater electrical potential and magnetic signature, pressure signature, radar cross section and actively emitted signals. [Ref 55] The vessel was designed based on the strength requirements as defined in "Det Norske Veritas, High Speed and Light Craft" rules. [Ref 87]

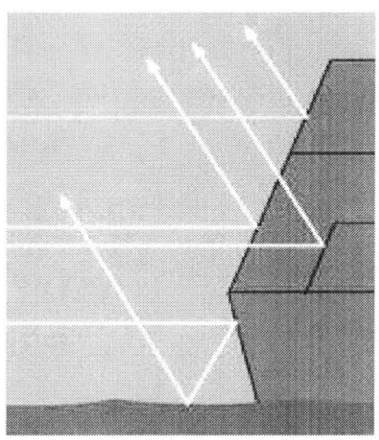


Figure 11: The extremely flat, outward-stopping CFRP hull of Visby results in controlled and favorable reflection of radar waves. [Ref 15]

The hull is designed on stealth principles with large flat angled surfaces. The stealth effects are the following:

1. Decreased detection, compliance homing weapon picture

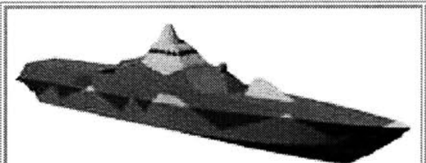
2. Increased countermeasures effectiveness

3. Smaller ECM gear

4. Less maintenance (sheltered equipment); corrosion protection is simpler

5. Carbon fiber has radar absorption properties. [Ref 59]

Table 1. Visby main characteristics [Ref 55]

	**Main Data**
Overall length	72.8 m
Beam	max 10.4 m
Displacement fully equipped	600 tonnes
Draught	2.4 m
Crew	43
Hull	CFRP sandwich
High speed	4 gas turbines prod. 16000 kW
Low speed	2 diesel engines prod. 2600 kW
Propulsors	2 water jet propulsors
Maximum speed	It is a secret, but well in excess of 35 knots

The vessel is built of sandwich-construction carbon fiber reinforced plastic (CFRP) (consisting of a polyvinyl chloride-PVC core with carbon fiber/vinyl ester laminate). The material provides high strength and rigidity, low weight, good shock resistance, low radar signature and low magnetic signature. The material dramatically reduces the structural weight (typically 50% of a conventional steel hull). [Ref 90] It provides also, high durability and good shock resistance, all at a feasible cost. This results in higher payload carrying capacity, higher speed or longer range. In order to meet special properties of Visby, special production methods were developed, such as advanced vacuum injection technique. [Ref 98]

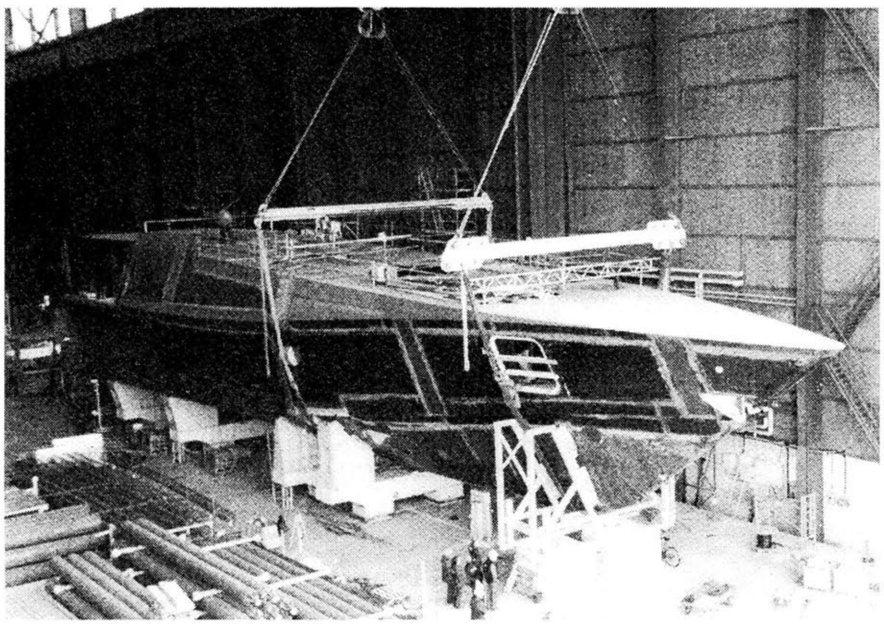


Figure 12. Sweden's YS2000 class corvette, the first known production naval stealth, takes shape at Kockums' shipyard on Karlskrona Island. [Ref 97]

Compared with traditional materials, the CFRP hull has a very good weight/strength/price ratio that does not drive overall cost in comparison with other materials. [Ref 16] It also gives a hull that is light, but still has excellent shock resistance properties. The hull also insulates heat, is nonmagnetic and the surfaces are very flat due to the production method. The advantages of using this material concept are numerous. [Ref 89] The major advantages are:

- High stiffness/weight ratio

- Flat panels, in order to create a low Radar Cross Section (RCS)

- Non-magnetic material

- Shock damping capacity. The CFRP-sandwich structure has excellent energy absorbing capacity

- Thermal insulation

- Low maintenance cost. As there is no corrosion on a CFRP-hull compared to a steel hull, there is only a small need for maintenance, which reduces the Life Cycle Cost (LCC) for the vessel

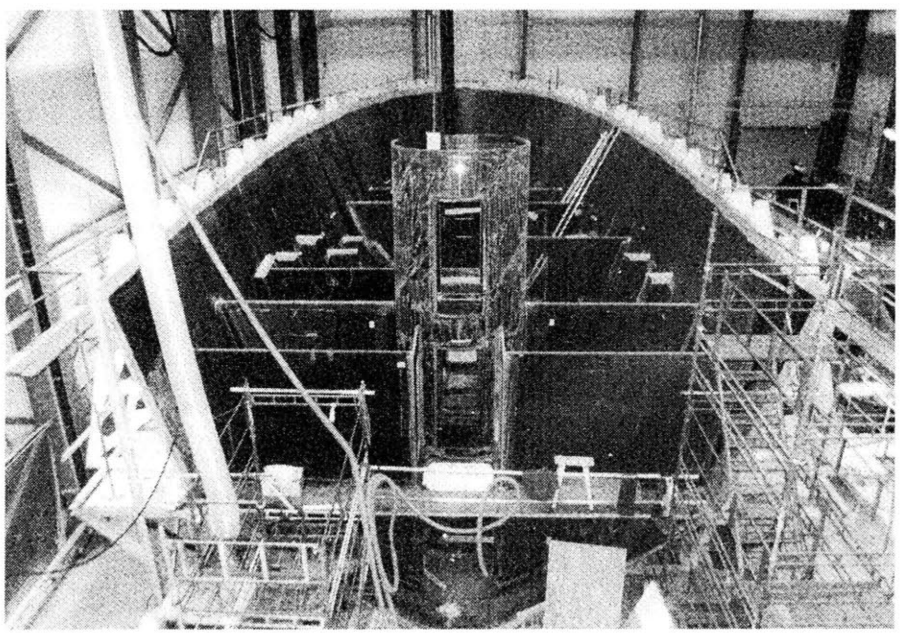


Figure 13. Sandwich type composite for Visby class, consisted of vinyl ester resin layers surrounding a polyvinyl chloride core containing carbon fibers. [Ref 97]

The hull is consisted of four main sections, fore, mid, aft and superstructure. Joining composite sections is much more complicated than joining steel ones. The method used for Visby was developed at Kockums and is based upon the KVASI vacuum-infusion method. The total cost estimated at $840 million for six (6) ships (from 1998 to 2007). Based on the Swedish composites and experience with GRP advantages are: small maintenance cost, no degradation due to aging and fatigue, damage is very limited in collisions and groundings and damage is easily repaired. [Ref 17] The use of carbon fiber is driven by low weight, RCS reduction, magnetic, IR, and EMI shielding requirements. The carbon fiber became a clear solution for high strength & stiffness, shock resistance, impact resistance. Low overall cost for carbon fiber in direct competition against aluminum and GRP. There will be also active monitoring of the hull stress to provide the crew with the condition of the hull at high speeds in rough conditions. [Ref 54]

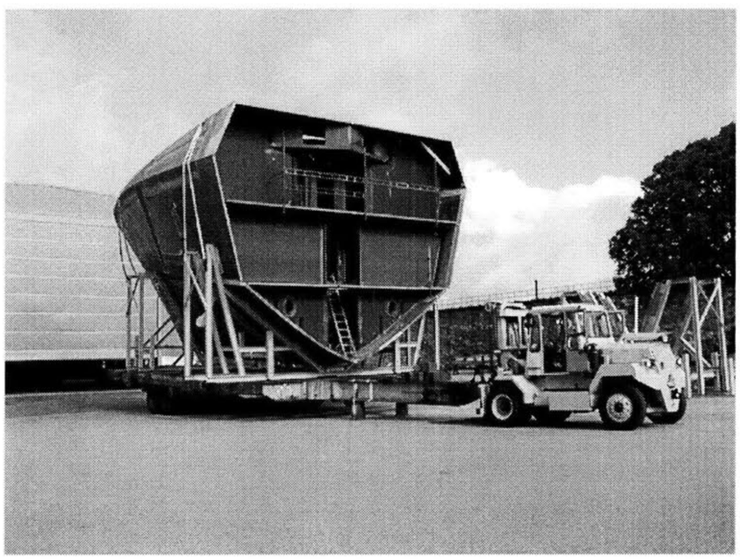


Figure 14: Bow section of the Visby-class corvette under transportation to the outfitting workshop. [Ref 103]

3 Materials

3.1 Types of composite materials

Advanced fiber-reinforced composite materials are formed by embedding high strength, high stiffness fiber materials within a surrounding matrix of a constituent material. [Ref 23] The fibers may be single filaments or multi-filament bundles, the latter being twisted together to form a yarn or tow. The fibers generally used are non-metallic and continuous and are identified as graphite, glass, Kevlar, silicon carbide, boron, or alumina. In addition to continuous fibers, there are also other types of reinforcements that are used in discontinuous reinforcement composites. Within the types of composite systems discussed, the term *advanced composite* is used to differentiate between those with high performance characteristics -generally strength and stiffness- as opposed to simpler types.

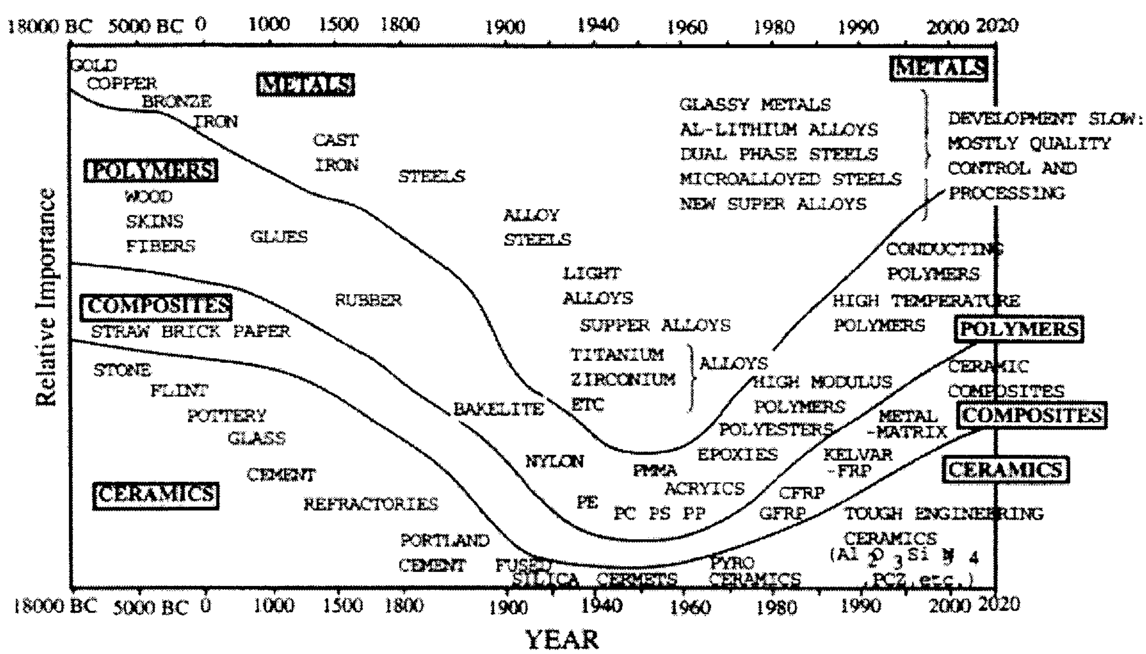


Figure 15. Evolution of materials for mechanical and civil engineering (Froese, F. H.,

"Aerospace Materials for the Twenty-first Century", Materials Design, originally prepared by Ashby, M. F. in 1987. [Ref 79]

The major classes of structural composites used today consist of polymer-matrix composites (PMC), metal-matrix composites (MMC), ceramic-matrix composites (CMC), carbon-carbon composites (C/C), and hybrid composites. Of these classes of composites, the PMCs are the most widely developed with a wide range of fabricated shapes and accepted commercial properties. These materials are characterized by their light weight, high strength and stiffness, corrosion resistance, and fatigue-resistant properties.

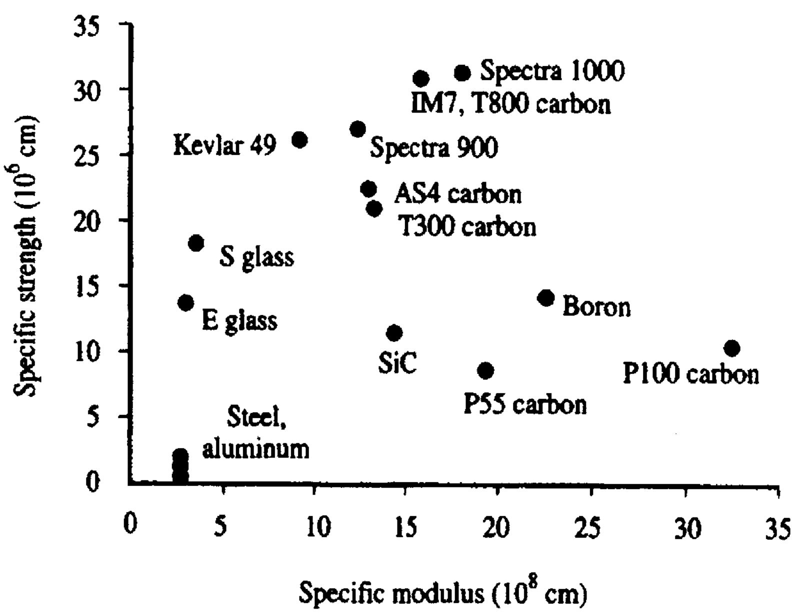


Figure 16. Specific modulus and specific strength for various engineering materials and fibers. [Ref 85]

MMCs are characterized by their higher temperature properties as compared to PMCs. CMCs offer the potential for even higher temperature structural applications when compared to the MMCs. C/Cs are superior in applications where very high temperatures occur and where thermal shock is a design factor. Hybrid composites represent the newest class of composites and include the use of a composite material with other composites or with other monolithic materials.

3.2 Constituents of Composite Materials

3.2.1 Fibers

Fibers are used to convey structural stiffness and strength to composite materials. Selection of fibers, specification of the form of the reinforcement and choice of the process by which the reinforcement is incorporated into the composite is set by the properties required in the composite material. Strength, stiffness and stress-strain properties of composites are a function of the volume fraction of fibers in the section of the composite, the matrix resin used and the directionality of the fibers with respect to the external loads. The volume fraction of fibers attained in the composite is a function of the form of the reinforcement and manufacturing process.

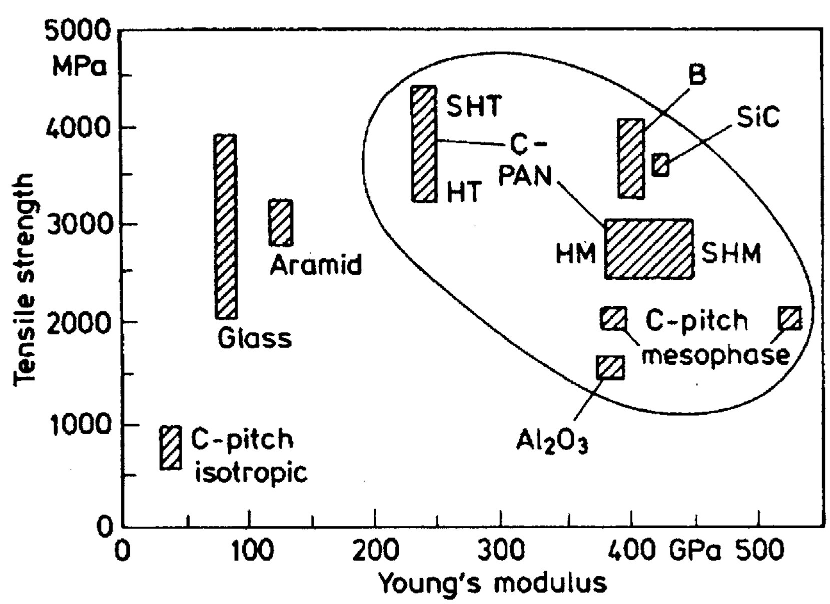


Figure 17. Comparison of different fibers [Ref 81].

3.2.1.1 Carbon fiber properties

Table 2 shows some properties of the main types of carbon fiber. In some ways carbon fibers can be thought of as midway between glass and aramids, the final fiber is inorganic, but arises from an organic precursor, and the fibers are composed neither of randomly oriented molecules nor linear chains.

Table 2. Typical properties of some grades of carbon fiber.[3]

		PAN[4] based		**Pitch Based**	
	"Low" modulus	*Intermediate modulus*	*High modulus*	*High modulus*	*Ultrahigh modulus*
Modulus (GPa)	230	294	400	520	720
Strength (GPa)	3.5	5.6	3.1	2.1	2.2
Strain (%)	1.5	1.9	0.75	0.4	0.3
Density	1.76	1.80	1.86	2.08	2.15

3.2.2 Resins

The selection of polymer resins for use in structural composites can be determined by a number of factors and should not be made without full consultation with materials suppliers and fabricators. Properties required are usually dominated by strength, stiffness, toughness and durability. Account should be taken of the application, service temperature and environment, method of fabrication, cure conditions and level of properties required.

3.2.2.1 Resin Development

Polyester has been the resin choice for composite hulls since the 1940's, only recently being supplanted by vinyl esters. Vinyl esters and polyesters are similar: they have the same cure

[3] The information shown above gives only the most general indication of properties for different types of carbon fibers, specific grades can vary widely from the values noted here. Potter, Kevin, "An Introduction to composite products", Chapman & Hall, London SE1 8HN, UK, 1997.

[4] Polyacrolonitrile

kinetics, use the same catalyst systems, and are compatible with the same glass fiber sizes and finishes.

As efforts to reduce weight and improve properties continue especially in the automotive industry, composites are becoming more widely used to replace metals. Vinyl ester resins are recognized for their strength and corrosion resistance and are being specified for an increasingly large number of automotive components. [Ref 91] Two areas where vinyl esters are meeting with success are: 1) where high temperature and corrosion resistance are needed and 2) where high strength and excellent fatigue properties are required.

3.2.2.2 Resin Systems

Polyester resin, by virtue of its relatively low cost and suitability for cold-cure, hand lay-up or spray-up application, continues to be the usual material in hull laminates. Vinyl ester resin, which costs about twice as much as isophthalic polyester, has superior toughness, water resistance and heat-distortion temperature and has been used in some high-performance hulls, particularly in United States. Epoxy resin offers superior mechanical properties but costs twice or three times as much as polyester and involves a more difficult laminating process. The main advantage of cold-setting phenolic resins is its high fire resistance and low smoke emission; its main weakness appears to be high void content caused by water vapor emission during cure and high water absorption when immersed. [Ref 6] Table 3 shows some properties of the three main types of matrix resins.

Table 3. Typical properties of various resin types.[5]

[5] The information shown above gives only the most general indication of properties for different types of carbon fibers, specific grades can vary widely from the values noted here. Potter, Kevin, "An Introduction to composite products", Chapman & Hall, London SE1 8HN, UK, 1997.

Material	Specific gravity	Modulus (GPa)	Tensile strength (MPa)	Strain to fail (%)	Poisson Ratio	Shrinkage on cure(%)	Max use (°C)
Polyester	1.2	3	60	2	0.36	7	65
Vinyl Ester	1.15	3.4	80	4	0.36	5	90
Epoxy low T	1.2	3.2	90	4	0.38	2	90
Epoxy high T	1.28	3.8	80	3	0.38	2	140
Phenolic	1.15	3	50	2	0.35	N/A	130

3.3 Advantages and disadvantages of marine composites

The application of FRP composites to marine structures offers the potential for significant weight, cost and signature reductions. The main advantages that marine composites offer are:

- **Ability to orient fiber strength** in the direction of maximum stress, thus providing the designer with the ability to economically optimize strength-weight calculations to a greater extent than with metals.

- **Ability to mold complex shapes** with relative ease and economy.

- **Low maintenance**: the non-corrosive nature of FRP generally results in much lower hull maintenance.

- **Flexibility**: the low modulus of elasticity of FRP is beneficial in storing energy from impact loads such as slamming.

Table 4 presents the relationship between the composite property and the advantage to the marine application.

Table 4. Advantages of composite properties. [Ref 38]

Composite Property	Advantage to marine Use
Corrosion resistance	Longer life of component and reduced maintenance
Lightweight	Greater payload capacity, increased depth, higher speeds, easier handling/installation
Monolithic Seamless Construction of Complex Shapes	Easier manufacturing of complex shapes, consolidation of parts, signature reduction
Near net shape and good finish	Reduced need for secondary machining, reduced material waste, reduced painting needed
Tailorability of design Properties	Improved performance of component
Non-magnetic	Signature reduction, reduced galvanic corrosion
Non-reflective	Reduced radar cross section
Inherently Damping	Radiated noise reduction
Radar/Acoustically Transparent	Improved radar/sonar performance
Low Thermal Conductivity	Improved fire containment
Multiple Domestic Sources	Availability of raw materials
Design Cascading Effect	Improved performance of one component can reduce size of or eliminate other system components

On the other hand there are several issues that need to be taken into consideration prior to entering the final stage of the applications mentioned at previous paragraphs. The main disadvantages of marine composites are:

- **Flexibility as a design constraint** for equivalent thickness: a FRP hull would deflect about 10 to 12 times as much as steel hull.

- **General issues:** Joining, Compressive strength, Creep, Vibration, Abrasion, Fuel Tanks, Quality Control, Lay-up, Assembly, Secondary bonds, Vulnerability to fire, Installation of systems.

Although high cost is a major factor, a number of technical issues also are holding back the broad introduction of composites into the large-structure marine market. Table 5 summarizes these challenges and opportunities:

Table 5. Challenges and opportunities in the application of composites to the marine industry. [Ref 44]

Military and Commercial

Thick sections
Compressive load behavior
High stress design
Nondestructive evaluation
Joints and joining
Repair
Fire performance
Moisture absorption
Ultraviolet radiations
Impact resistance
Scaling/modeling
Reliability
Residual stress effects
Smoke and toxicity
Creep/stress rupture

Primarily Military

Shock performance
Electromagnetic radiation
Acoustic behavior
Ballistic performance

3.4 Material Selection

A popular philosophy in material selection is to assure that the material will behave at least as well as assumed in design calculations. For example, in tubular joints of offshore structures this means that the material must be able to accommodate large amounts of plastic deformation without fracture [Ref. 30].

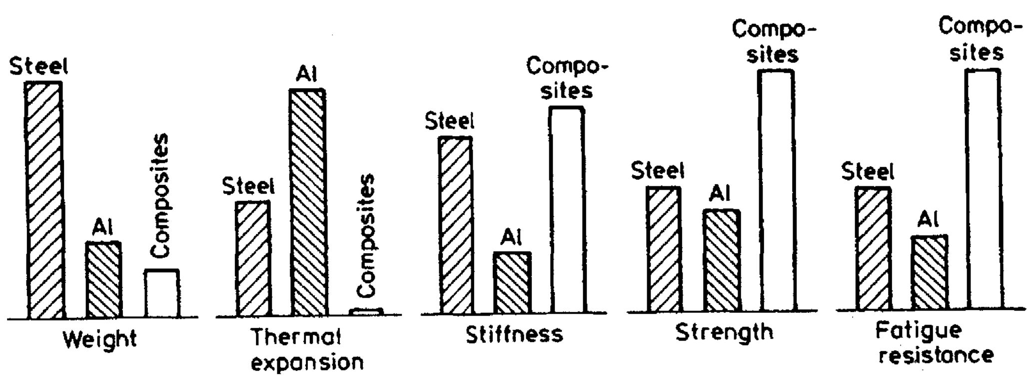


Figure 18. Comparison between conventional monolithic materials and composite materials. [From Deutsch (1978)] [Ref 81]

This is an important trade-off to be considered in material selection. To decrease the weight of the structure, a material with higher yield stress, i.e., a stronger material, will often be chosen. [Ref 43] There is, however, often an inverse correlation between the strength and the fracture resistance, or toughness, of a material. When fabricating with composites, a major determining factor in the control of product quality is the fact that the material itself is actually blended and compounded on-site by skilled or semi-skilled laborers. [Ref 25] This is not the case with steel: steel materials are fabricated in raw material production situations with numerous quality-control systems closely monitoring the process. During the fabrication of composite hulls, materials must be brought together, metered, thoroughly mixed, and de-aerated by a team of fabricators. This is radically different from construction of hulls and superstructures with steel products. [Ref 5]

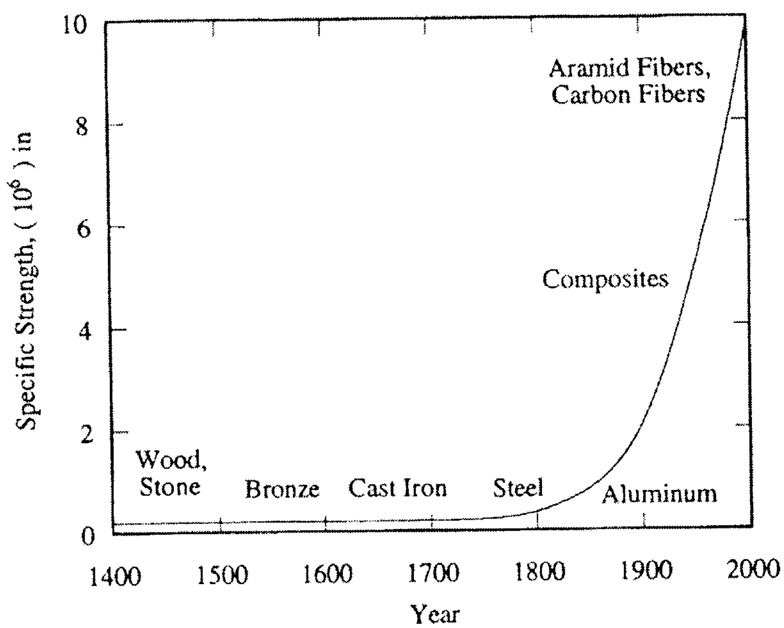


Figure 19. Specific strength as a function of time of use of materials. (Source: Reprinted from *Advanced Materials and Processes*, June 1991. Copyright 1991, ASM International.) [Ref 2]

3.5 Fibers and Resins Selection

3.5.1 Fiber Selection

There exist several different types of fibers in marine structures. Among them, the ones that presented excellent performance and major advantages are the glass and carbon fibers. These two fibers were considered as the candidate fibers for this study. [Ref 93] Table 6 presents raw fiber properties.

Table 6. Raw Fiber Properties [Ref 9]

Fiber	**Tensile Strength ($psi x 10^3$)**	**Tensile Modulus ($psi x 10^3$)**	**Ultimate Elongation**	**Cost, US $/lb (2001)**	**Cost, US $/lb (1994)**
E-glass	500	10.5	4.8%	0.92-2.00	0.8-1.2
S-glass	665	12.6	5.7%	6-10	4
Kevlar®	525	18	2.9%	14-20	16
Spectra® 900	375	17	3.5%	NA	22
Carbon	350-700	33-57	0.38-2.0%	8-30	17-450

3.5.1.1 Glass fibers

In the broad composites industry, the vast majority of all fibers used are glass. These fibers provide the strength advantage that glass-reinforced composites have over unreinforced plastics. With high strength and stiffness compared to the plastic, the glass fibers carry the loads imposed on the composite, while the resin matrix distributes the load across all the fibers in the structure. Depending upon the glass type, filament diameter, sizing chemistry and fiber form, a wide range of properties and performance can be achieved. [Ref 39]

Electrical or E-glass is so named because its chemical composition makes it an excellent electrical insulator. High-strength glass is generally known as S-glass in the United States, R-glass in Europe and T-glass in Japan. S-glass has appreciably higher silica oxide, aluminum oxide and magnesium oxide content than E-glass, and typically is 40 to 70 percent stronger than

E-glass. [Ref 57] Both E-glass and S-glass lose up to half their tensile strength as temperatures increase from ambient to 1,000°F, although both fibers still exhibit generally good strength in this elevated temperature range. Its strand tensile strength is 700ksi, with a tensile modulus of 14 Msi. [Ref 24]

The most common reinforcement material in marine application is still E-glass fiber, which has a good ultimate tensile strength, about 2200 MPa and an ultimate tensile strain of about 2.5 %. The ultimate strength of glass fibers is more or less constant between -50°C and 300°C. The most common type of glass fiber in structural design is E-glass, which has good resistance against moisture and chemical aggression.

Epoxy resin is definitely the most common matrix system for carbon fiber laminates that are used in space industry applications. Epoxy is used as a pre-preg system. For large structures, e.g., ship structures of 40-50 m in length, the pre-preg technique will cause big problems since the whole structure must be post cured in an autoclave at a temperature exceeding 80°C. For smaller structures and smaller vessels a wet lay-up system can also be used.

However, in Sweden the health authorities impose very strict limitations because uncured epoxy resin can cause allergic problems. Therefore, according to law, other material must be selected if it is possible.

3.5.1.2 Carbon fibers

Generally, carbon fibers exhibit higher tensile strength and stiffness than do their glass counterparts. However, the cost of these fibers greatly exceeds that of glass fibers.

Carbon fibers have ultimate tensile strength of about 4000 MPa and an elongation at break of 0.9-2%, depending on the type of carbon fiber. The use of carbon fiber in combination with glass fiber may be a good solution, but has to be carefully analyzed since the carbon fibers will carry most of the load in the hybrid laminate. If the structure is overloaded, the carbon fibers will break as a first-ply failure and the glass fibers with their much lower strength, might not be able to carry the load and a total failure may result.

A structure made entirely of carbon fiber is therefore a much simpler solution, which can also be cost effective if the total cost, which includes both material cost and labor cost, is taken into consideration. The amount of reinforcement when using carbon fiber can be reduced to such an extent that the much higher price of carbon fiber could be compensated. The new type of high-strength carbon fiber (T700) with higher elongation at break (2%) also shows excellent impact properties.

Tests have been made where a sharp steel cube is pressed into FRP-sandwich panels with different laminate types. From the table below it can be seen that a 2-mm thick laminate built up with rubber-modified vinyl ester and carbon fiber gives almost double the failure load as a 6 mm thick laminate built up with normal polyester glass fiber.

Table 7. Impact strength of different laminates. [Ref 32]

Type of reinforcement	Matrix	Laminate thickness (mm)	Max. load (kN)
Glass fiber 3x 800/100	Polyester	4.5	7.1
Glass fiber 3x 600/300	Polyester	4.8	5.4
Glass fiber 4x 800/100	Polyester	6.0	9.5
Glass fiber 4x 800/100	Vinyl ester	2.0	15.1
Carbon fiber 3xDBT700	Vinyl ester	3.0	20.4
Carbon fiber 3xDBT700	Epoxy	3.0	18.8
Carbon fiber 2xDBT700 + Aramid	Epoxy	3.5	13.9

The Toray T700 type of carbon fiber in combination with a rubber-modified vinyl ester demonstrates almost the same mechanical laminate properties, tensile strength, compressive strength and delamination strength as for laminates built up with epoxy. The carbon materials normally have a fiber sizing, which is suited for epoxy but is also suitable for vinyl ester. Due to the increasing use of carbon fiber in both marine and civil applications Toray has now developed a special size of carbon fiber, which is better suited for vinyl ester. This new fiber sizing, that will soon will available, has increased the delamination strength of the vinyl ester laminate by up to 25% compared to the earlier type of fiber sizing.

3.5.1.3 Other fibers

Depending on application requirements, a hybrid form combining carbon, boron or aramid fibers with glass fiber can improve overall performance of the composite and costs less than a composite relying only on advanced fibers. Another very promising option is basalt fiber, currently produced only in limited quantities in the Ukraine and Russia, but expected to be manufactured in the United States in the near future. Stiffer than glass for the same weight but not as stiff as carbon, basalt fiber exhibits high tensile strength (506,000 psi), very high heat resistance (operating temperatures of 1,800^{0}F) strong alkali resistance, high impact strength and low moisture absorption.

3.5.2 Resin Selection

Engineers have a substantial selection of polymer matrix resins to choose from designing and fabricating glass-reinforced composite parts. These resins fall into two categories, based on polymer chemistry: thermoset and thermoplastic. The majority of resins used in the composites industry are thermosets, although applications for thermoplastics are growing. The cost tradeoffs between thermosets and thermoplastics are physical properties, handleability, processing temperature and cure time. Each type of resin offers benefits for particular applications. For this study, the candidate resins are vinyl ester and epoxy.

3.5.2.1 Vinyl Ester resin

Vinyl ester resins may be derived from backbone components of polyester or urethane resins but those based on epoxide resins are of particular commercial significance. They resemble polyesters in their processing with use of styrene as a reactive diluent, allowing cold curing by a free radical mechanism with initiation through a peroxide catalyst and cobalt salt accelerator.

These resins offer a bridge between lower-cost, rapid-cure and easily processed polyesters and higher-performance epoxy resins, described in the following paragraph. Compared to polyesters, vinyl esters shrink less and absorb less water, and are more chemically resistant. The performance of vinyl ester surpasses that of polyester resin in applications like chemically corrosive environment and structural laminates, in which a high degree of moisture resistance is desired.

3.5.2.2 Epoxy resin

Epoxy resins are widely used in applications such as structural aerospace components (usually with carbon fibers). Epoxies are more expensive than vinyl esters, but shrink less and have higher strength/stiffness properties at moderate temperatures. Other advantages of epoxies include excellent corrosion resistance and adaptability to most composite manufacturing processes.

3.6 Matrix Selection

From all the possible combinations between fibers and resins selected above, the carbon/epoxy matrix was not included in the final matrix selection due to the incompatibility between these two constituents and the requirement of huge molds in order to produce this material for large applications. Therefore, the final matrices selection consists of the following:

- Carbon fiber with Vinyl Ester resin
- Glass fiber with Vinyl Ester resin
- Glass fiber with Epoxy resin

3.7 Material Properties

In fact, one of the major advantages of composites is the complementary nature of the components. For example, thin glass fibers exhibit relatively high tensile strength, but are susceptible to damage. By comparison, most polymer resins are weak in tensile strength but are extremely tough as well as malleable. The combination of these materials can be more useful than either of the individual components. Experimental results for the vinyl ester based composites were not available, therefore they were calculated theoretically by using an adjustment factor, which is coming from the comparison between the theoretical and experimental properties of the epoxy based composites. This method is thoroughly described in Bekiaris, 2000.

Table 8. Properties of selected matrices. [Ref 74]

Property	Carbon/ Vinyl Ester	Glass/ Epoxy	Glass/Vinyl Ester
Axial Young's Modulus (GPa)	181	38.6	38.6
Transverse Young's Modulus (GPa)	10.25	8.27	8.23
Poisson's Ratio	0.28	0.26	0.26
Shear Modulus (GPa)	7.9	4.14	8.86
Longitudinal Tensile Strength (MPa)	1500	1062	1062
Longitudinal Compressive Strength (MPa)	1225	610	496
Transverse Tensile Strength (MPa)	46	31	35.56
Transverse Compressive Strength (MPa)	282	118	135.32
Shear Strength (MPa)	28.63	72	60.78
Specific Gravity	1.6	2.11	2.086

3.7.1 Material Properties for Stiffeners, Girders, Frames

We can perform the structural analysis in one direction –due to the fact that the loads considered result only in axial stresses for the frames, stiffeners and girders- and the stresses are both tensile and compressive. No matter if the material is orthotropic, it can be considered isotropic based on the assumption stated above. Therefore, only unidirectional fibers were considered for this type of structural elements. Table 9 presents the properties of the composite materials used for frames, stiffeners and girders.

Table 9. Material properties for the selected matrices for the stiffeners, girders and frames. [Ref 74]

Property	Carbon/ Vinyl Ester	Glass/ Epoxy	Glass/ Vinyl Ester
Young's Modulus (Gpa)	181	38.6	38.6
Poisson's Ratio	0.28	0.26	0.26
Yield Strength (MPa)	1225	610	496

3.7.2 Material properties for plates

The assumption that the plates were fabricated by symmetric and balanced laminates was made (stacking sequence $[0/\pm45/90]_{symmetric}$). Table 10 presents the properties for the selected composite matrices used for the plates.

Table 10. Material properties for the selected matrices for the plates. [Ref 74]

Property	Carbon/ Vinyl Ester	Glass/ Epoxy	Glass/ Vinyl Ester
Young's Modulus (Gpa)	70.27	18.97	22.36
Poisson's Ratio	0.29	0.27	0.138
Yield Strength (MPa)	405.4	254	218.6

3.8 Architecture of advanced composites

The architecture, or fiber arrangement, of advanced composites can take many forms. Traditionally, advanced composites consisted of plies of material, either unidirectional tape or woven fabric, preimpregnated with the matrix material and laminated together to form the composite structure. This type of construction is classified as a two-dimensional (2-D) architecture since the reinforcement is oriented in a planar, or 2-D, fashion. The fiber architecture permits the in-plane strength and stiffness of the material to be tailored by preferentially orienting the fibers in the direction of loading. [Ref 33] If the loading is not limited to within the plane of the material, however, the 2-D architecture must rely on the matrix of the composite for the strength and stiffness required to maintain the structural integrity of the material.

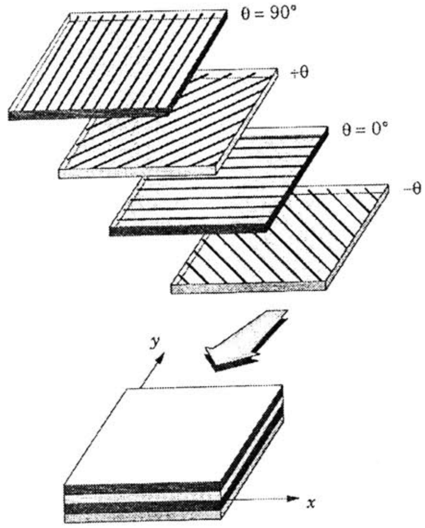


Figure 20. A laminate made up of laminae of different fiber orientations. [Ref 2]

Because of the lack of reinforcement between layers interlaminar strength is generally on the order of the unreinforced matrix material that is generally relatively low compared to the in-plane shear properties of the composite. [Ref 19] The discrete layers of the reinforcement also allow for the propagation of damage through the structure by means of delamination because of the relatively low interlaminar strength. This has been a classic problem associated with highly loaded composite structures manufactured by a lay-up process. The elimination of this type of failure can be accomplished by providing reinforcement through the thickness of the composite.

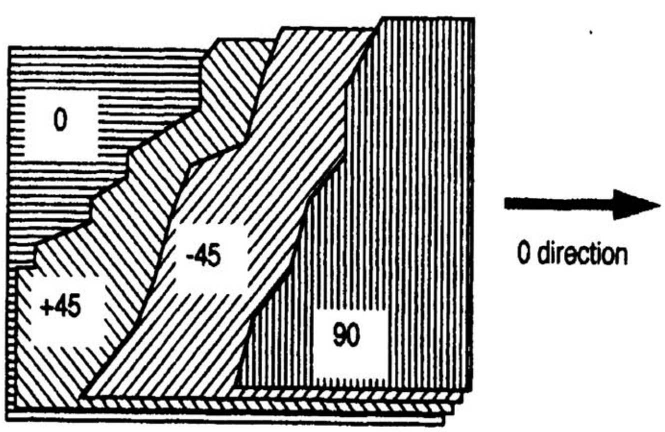


Figure 21. Convention for identifying ply directions. [Ref 80]

Three-dimensional (3-D) reinforcement in composites can take many forms. The 3-D orthogonal architecture is fabricated by adding through the thickness, or z-direction, reinforcing fibers that are normal to the in-plane reinforcement such as in stitched laminates or 3-D woven fabrics. This architecture is limited to providing reinforcement in the three principal directions, x, y, and z, although it is possible to orient the fibers at off-axis angles in the x-y plane to increase the shear capability of the material in this plane. The orthogonal architecture limits the tailorability of the material because the out-of-plane reinforcement can only be placed in the material normal to the in-plane reinforcement. This limitation reduces the in-plane performance of a material with a fixed fiber volume fraction because the z-direction reinforcement does not contribute, and in fact is a detriment, to the in-plane strength and stiffness. [Ref 37]

Two-dimensionally reinforced composites are currently the state of the art for composite structures. Important advantages include high tolerance to impact damage as well as the ability to inhibit the propagation of damage if it does occur, superior interlaminar shear, fatigue, and open hole tension and compression performance. The applications for composite materials in the marine world are essentially limitless. Some specific components that are currently under investigation for near term application are piping and fittings, valves, pumps, heat exchangers, ventilation ducting, and propulsion shafting. Advanced composite materials offer many advantages over the conventional metals when used in marine structures. [Ref 21] They can reduce weight, offer excellent corrosion resistance, improved damping characteristics, and they are nonmagnetic.

Table 11: Perceived limitations and solutions to using FRP in ships. [Ref 95]

Limitations of FRP	*Old Argument*	*Solution/Current Application*
Hull Stiffness	Stiffness is only 20% that of steel.	Overall stiffness is basically a combination of materials modulus AND section-both can be increased to get suitable stiffness.
Abrasion	FRP has low resistance to abrasion around cargo handling, in the hull sides for docking, in the hull bottom for grounding.	Use a Kevlar felt in areas where high abrasion is expected.
Fuel Tanks	Laminate flaws which allow fuel to migrate through the structure preclude integral tanks.	Use two layers of 1oz mat and a veil to create a resin-rich barrier around the tank.
Lay-up	Hand lay-up is inadequate, prone to errors, and slow.	Impregnators are well-developed, strong adhesives to bond sections.
Secondary Bonds	Secondary bonds are the weakest part of the technology.	Guidelines are well-developed, very strong adhesives available.
Fire Resistance	Resins are flammable, fire retardant resins are weak, structures are heat sensitive.	New, fire retardant resins are stronger and conducive to new processing methods, combination of active and passive fire protection reduce the risk.

3.8.1 Sandwich Construction

Composite sandwich panels with FRP faces and low-density foam cores are fast becoming the structural material of choice in the marine small craft industry. This is particularly true for high performance applications, where naval architects strive to expand the craft operational envelope by improving the hull structural performance. Most often this is accomplished with a simultaneous reduction in the hull weight. In the commercial sector, the goal in expanding this envelope is typically higher craft speeds with smaller, more efficient power plants. For military applications, the goal is most often a higher payload capacity or combination of the two. [Ref 41]

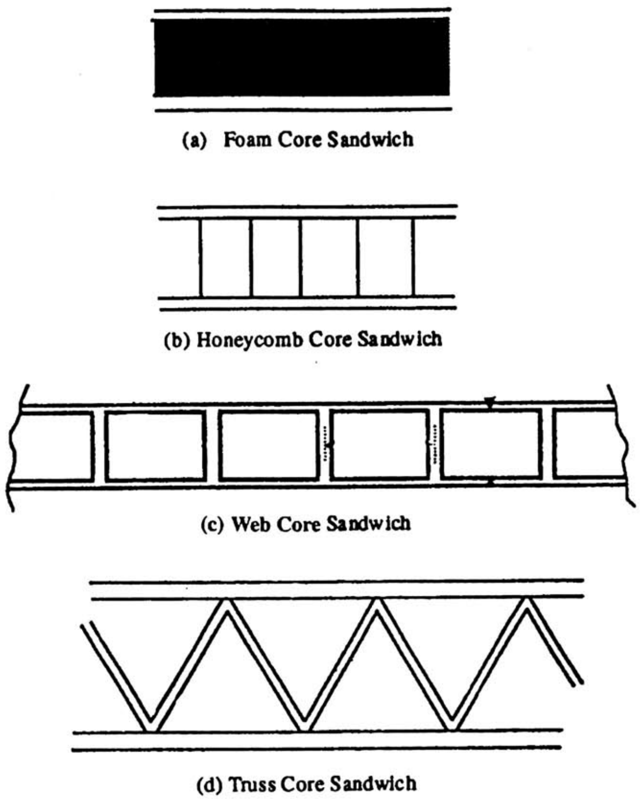


Figure 22. Types of Sandwich Composites. [Ref 84]

Sandwich construction may be defined as a three-layer type of construction where a relatively weak, low-density core material supports and stabilizes thin layers of high strength face material. Its typical features, namely high strength-thin and low strength-thick materials, interfaces, bonding and load transfer suggest that each of the layers will perform according to its material characteristics and laminate position. [Ref 42] Most of the theories used for the analysis of such structures are based either on the Kirchhoff or Mindlin assumptions. The first model does not account for transverse shear deformations while the second assumes a first order shear deformation behavior. However, both models consider for all the layers a common and unique rotation of the middle part.

The type of core design or material is a matter of great importance for sandwich constructions. Table 12 presents properties of various foam core types, while Table 13 presents properties of honeycomb core materials, which are currently widely used in modern advanced structures. Finally, Figure 23 presents honeycomb structure and specification with its elements.

Table 12. Typical properties of various foam core types.[6]

Material	Specific gravity	Compression		Shear	
		Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)
PMI	0.07	92	1.5	45	1.3
PVC	0.08	50	1.1	25	0.8
PVC	0.19	160	4.0	50	2.4
PU	0.10	39	1.0	10	0.6
PU	0.19	83	3.0	30	1.4
Syntactic	0.8	2600	44	1000	21

Sandwich construction results in lower lateral deformations, higher buckling resistance, and higher natural frequencies than do other constructions. Thus, for a given set of mechanical and environmental loads, sandwich construction often results in a lower structural weight than do other configurations. The U.S. Navy is using honeycomb-sandwich bulkheads to reduce the ship weight above the waterline.

[6] The information shown above gives only the most general indication of properties for different types of foam cores, specific grades can vary widely from the values noted here. Potter, Kevin, "An Introduction to composite products", Chapman & Hall, London SE1 8HN, UK, 1997.

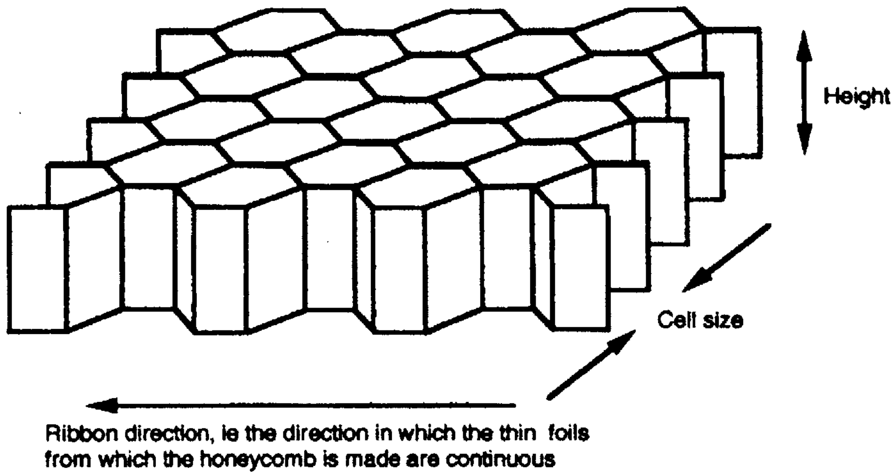


Figure 23. Honeycomb structure and specification. Elements of the specification of honeycomb: (1) material; (2) bulk density; (3) cell size; (4) height; (5) thickness of cell wall (this is not always defined, it effectively fixes the bulk density if (1) and (3) are fixed)[Ref 80]

Table 13. Typical properties of some grades of honeycomb core.[7]

Specific gravity	*Stabilized*	*Compression*		*Plate*	*Shear*	
			L - Direction		*W - Direction*	
	Modulus (MPa)	*Strength (MPa)*	*Modulus (MPa)*	*Strength (MPa)*	*Modulus (MPa)*	*Strength (MPa)*
0.05	0.52	2.1	0.31	1.4	0.15	0.9
0.072	1.03	3.9	0.48	2.3	0.21	1.52
0.098	1.65	7.2	0.68	3.8	0.28	2.21
0.130	2.41	10.2	0.93	5.0	0.37	3.14

[7] The above figures would be expected to be in the right range for either aluminum or aramid paper honeycomb of hexagonal format and vary little with cell size. The information shown above gives only the most general indication of properties for different types of honeycomb, the properties of specific grades can be identified from manufacturer's datasheets. Potter, Kevin, "An Introduction to composite products", Chapman & Hall, London SE1 8HN, UK, 1997.

3.9 The Marine Environment and Ageing

The main threat to structures operating in a marine environment is usually perceived to be water, but more generally their durability may be reduced by [Ref 65]:

- Mechanical loads (wave impact, erosion, hydrostatic pressure);

- Physical degradation (differential swelling due to moisture, thermal effects);

- Chemical attack (hydrolysis of resin, effect of hydrocarbons);

- Biological attack (fouling, biologically induced corrosion).

Environmental effects on composites have been widely studied. Data have been collected for high performance aerospace composites, generally using varying relative humidities rather than immersion, while glass reinforced materials have been studied for chemical engineering applications. A large database has also been collected for naval applications, with over 20 years immersion in some cases. One of the key issues in estimating long term ageing effects is the validity of accelerated test procedures. The use of increased temperature to accelerate testing times does not necessarily affect the different ageing mechanisms in the same way. Table 14 presents the mechanisms, which can intervene during ageing in water.

Table 14. Aging mechanisms.

Reversible effects	**Inversible effects**
Plastification	Hydrolysis (molecular chain breakage)
Swelling	Leaching out of material Cracking and delamination

The time to the onset of hydrolysis is a critical parameter for durability predictions but few reliable data exist for commonly used resins. The enhancement of degradation by applied stress has been examined by several authors and reviewed.

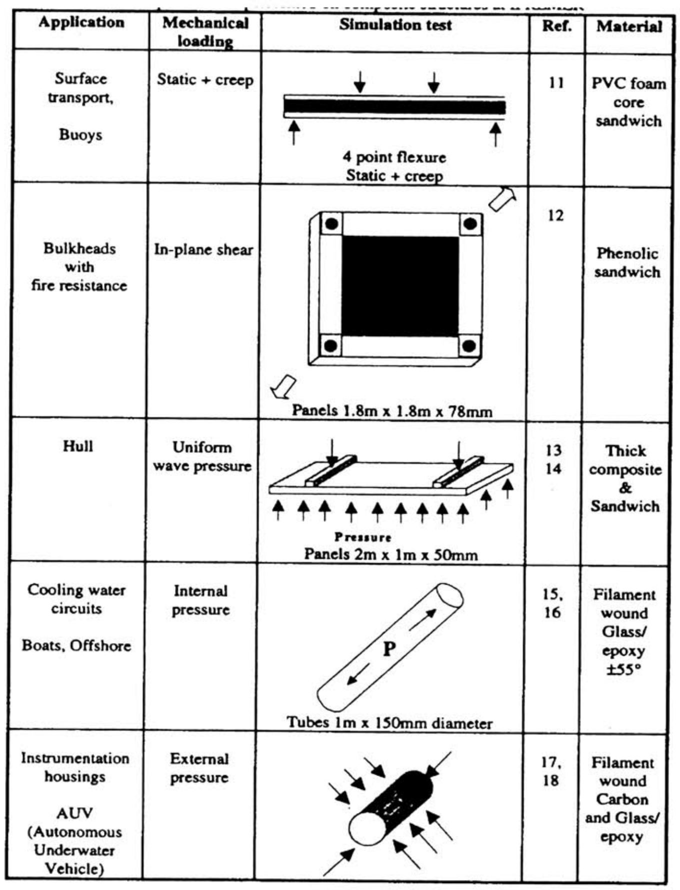
A second type of degradation, which has been the cause of much controversy in the pleasure boat industry, is blistering. The appearance of blisters results from osmosis across the gel-coats used to protect composite hull structures. The phenomenon has been known for many years, and particular combinations of manufacturing conditions, resin chemistry, fiber coating and service conditions have resulted in blisters appearing in very short times. While initially an aesthetic problem, delamination and property loss may follow if blistering is not treated. Repair of blistered hulls can be very expensive as thorough drying is recommended. A recent study [Ref…] has examined the kinetics of blister propagation through accelerated test. It was concluded that the probability of blistering appearing during the 20-year lifetime of a boat with orthophthalic polyester laminate and gelcoat was high, whereas for isophthalic polyesters this was much reduced unless the gelcoat was thin.

3.10 Fire Performance

The composite structures used in naval applications tend to be large, complex, and thick. As such, the use of room or low temperature non-autoclave cure resins is desirable. The U.S. Navy is presently using fire retarded (brominated) vinyl ester resin for some topside composite structures. These composites are produced by vacuum assisted resin transfer molding. An extensive effort is underway to fully characterize the fire performance of vinyl ester based solid and sandwich (balsa core) composites for many ongoing topside applications. Fire safety goals and material performance criteria for specific applications in both surface ships and submarines are under examination. [Ref 92]

There is a need of further understanding the way composite materials behave during shipboard fires. The Navy has developed a military standard for qualification of composite materials to be used in submarines. Additional theoretical and experimental work is needed to supplement our knowledge of how composite material systems perform at elevated temperatures.

The single factor that has limited the application of composite materials on ships is the unknown performance of various systems during a fire. All organic matrix material will burn at a given temperature. This not only compromises the structure's mission capabilities, but also contributes fuel to the fire. On the other hand, composites act as excellent insulators, which can serve to contain fires to a given space. [Ref 49]



Application	Mechanical loading	Simulation test	Ref.	Material
Surface transport, Buoys	Static + creep	4 point flexure Static + creep	11	PVC foam core sandwich
Bulkheads with fire resistance	In-plane shear	Panels 1.8m x 1.8m x 78mm	12	Phenolic sandwich
Hull	Uniform wave pressure	Pressure Panels 2m x 1m x 50mm	13 14	Thick composite & Sandwich
Cooling water circuits Boats, Offshore	Internal pressure	P Tubes 1m x 150mm diameter	15, 16	Filament wound Glass/ epoxy ±55°
Instrumentation housings AUV (Autonomous Underwater Vehicle)	External pressure		17, 18	Filament wound Carbon and Glass/ epoxy

Figure 24. Examples of tests performed on composite structures at IFREMER [Ref 83]

Composite structures, like their metallic counterparts, will show a decrease in load carrying capability before failure as temperature increases. After a fire, there may also be some permanent resin pyrolisis or delamination that can render a structure unsuitable for service. Volume of smoke produced by a burning composite, as well as the combustion by-products themselves, may be independent of the material's flammability performance. Combustion by-products may also be corrosive in nature, attacking metallic structure and electronic equipment that might not even be near the scene of the fire.

The breakthroughs have to come with development of composite material systems that meet all the flammability criteria or in case-by-case acceptance of composite materials that do not meet all the criteria but provide reasonable fire performance for specific application. Fire safety for marine materials may be broken down into five areas of primary concern: fire propagation (whether a material supports combustion), fire redundancy (related to the spread of the flame), fire containment (whether the material can serve as a fire barrier), smoke and toxicity characteristics (contribute or detract from escape and firefighting efforts) and fire endurance (how well the material maintains its structural integrity). Materials on fire should not generate untenable conditions quickly.

3.10.1 Time-Temperature effects on composite materials

In addition to the effects of temperature and moisture on the short-time properties, if a structure is maintained under a constant load for a period of time, then creep and viscoelastic effects can become very important in the design and analysis of that structure. Creep and viscoelasticity can become significant in any material above certain temperatures, but can be particularly important in polymer matrix materials whose operating temperatures must be kept below maximum temperatures of 250°F, 350°F, or in some cases 600°F for short periods of time. In general the existing data for the composite materials are not sufficient to characterize them accurately.

3.11 Corrosion

Marine engineers have sought effective and economical means to protect ship hulls and marine structures from the ravages of seawater and marine life for centuries. The ideal hull material for ships of various sizes and duties has been the subject of intense study, and a variety of hull materials are being used or have been evaluated.

3.12 Maintenance and Repair

Maintenance of the structure involves inspection and painting. Inspection of a FRP-sandwich structure is more difficult than that of steel or aluminum structure. Repair of FRP-sandwich structures requires good environmental conditions, but the procedures are relatively straightforward. There are a number of guidelines for repairing FRP and FRP-sandwich structures, but they are not standardized in the same way as for steel and aluminum, due to the wide variety of material combinations available and recent development of the materials. Trained personnel can handle small field repairs quickly and easily. Major repairs require shore based facilities and experienced personnel dealing with composite materials. [Ref 89]

3.12.1 Reinforcements

E-glass fiber, because of its low cost and ease of use in chopped strand mat (CSM), woven roving (WR) and unidirectional tape form, remains far the most used reinforcement. S-glass, produced mainly in USA, and its European equivalent R-glass, offer substantially higher strength at a cost, which is 5 to 10 times higher than that of E-glass. Carbon fibers, which are now used extensively in aerospace vehicles, are also finding increasing application in high-performance marine structures and offer a prospect of dramatic savings in weight-critical hulls such as hydrofoils and hovercraft. Because of the high cost of carbon fiber (20 to 40 times that of E-glass) and the low impact strength of CFRP laminate it will normally be desirable to hybridize carbon with glass fiber in hull construction. Aramid (Kevlar 49) fibers have very high specific tensile strength but have a low compressive strength, which undermines their effectiveness in shell structures under bending and buckling conditions. Kevlar has proved particularly effective in withstanding ballistic impact, where energy is absorbed primarily by transmission of tensile shock waves along fibers, and have also proved effective in very thin shells where lateral loads and impacts are resisted by a membrane action. In thicker laminates, glass reinforcements provide superior performance. Kevlar reinforcement should always be considered for high-performance structural components in which loading is predominantly tensile, including shear members with a preferred load direction where shear can be carried by diagonal tension. [Ref 6]

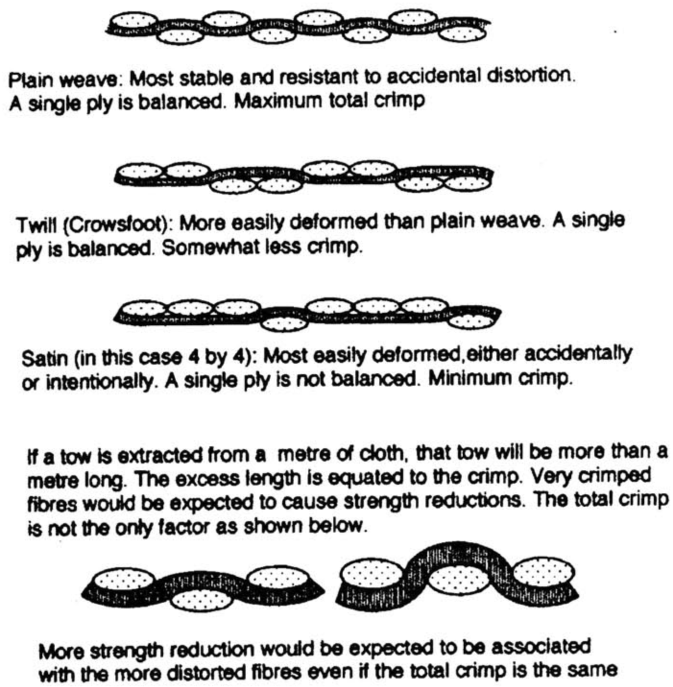


Figure 25. Cross-sections through various woven cloth types. [Ref 80]

3.12.2 Hybrid reinforcement

Much scope exists for optimizing the balance between stiffness and static, fatigue and impact strength combination of glass with carbon or Kevlar fibers. [Ref 6] There are several classes of hybrids: those that mix the fiber types at a very fine (or intimate) scale so that, for example, a glass fiber may lie next to a carbon fiber, those that mix tows within a single ply and those that intermingle plies of different fibers within the lay-up. For completeness, structures in which different reinforcement are used (e.g. glass mat and glass cloth) can be considered as other forms of hybrids. The long term properties of hybrids, such as environmental resistance, fatigue and stress rupture, have been much less studied, but are likely to be dominated by the properties of the fibers rather than by interaction effects and concepts of synergy. Hybridization can be a very useful way of balancing requirements for strength and stiffness in various directions at minimum cost, or between bending and in plane properties for layered hybrids.

4 Structural Analysis

Structural analysis must begin with the loads. However, because of the uncertainties associated with loads, they can never been known with precision. The practice has been to specify standard loads to be used in design. For ship structures, these loads have not been defined in terms of the highest loads anticipated in the life of a ship, but rather as some reasonable high loads, although there is no uniform method for defining what could be considered as reasonable.

Increased emphasis should be placed on developing more rational reliability-based structural designs due to the fact that marine structures are dependent to several factors, as presented at Figure 26. In order to complete the structural analysis of a structure and evaluate its performance all the relationships between the structure and these factors have to be encountered. For this study a preliminary structural evaluation was performed.

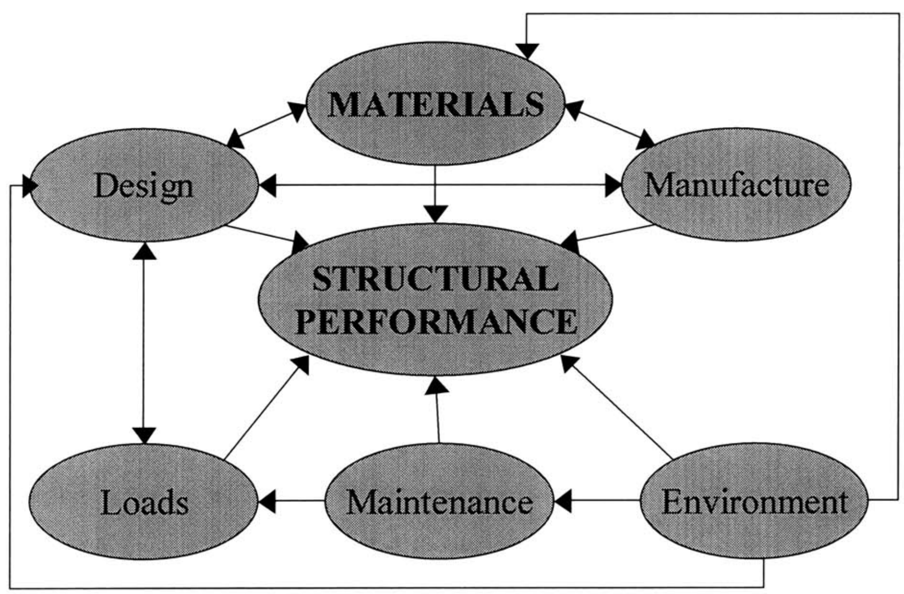


Figure 26. Parameters affecting structural performance in the marine environment.

4.1 Selection of a Ship

The application of composite materials was evaluated for a naval surface ship due to the complicated nature of this structure. [Ref 100] Specifically, a midship section of a DDG ship of the United States Navy (USN) was selected. Figure 27 presents the cross section of this midship section. The length of this section is 14.13m. The main characteristics of the DDG are presented at Table 15. The dimensions of the scantlings were derived from the USN Advanced Surface Ship Evaluation Tool (ASSET). [Ref 52]

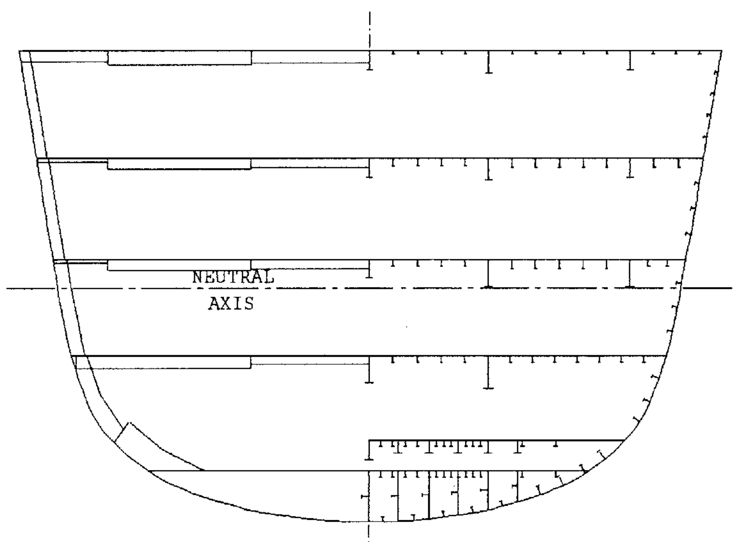


Figure 27. Midship section of a DDG

Table 15. Main characteristics of the selected structure.

Length Between Perpendiculars (m)	142	Prismatic Coefficient	0.615
Length Overall (m)	150	Max Section Coefficient	0.822
Beam (m)	18	Waterplane Coefficient	0.791
Beam at Weather Deck (m)	20.25	Light Ship Displacement (lton)	6686
Draft (m)	6.3	Full Load Displacement (lton)	8672
Depth at Station 10 (m)	12.75	Hull Structure Weight (lton)	2100

4.2 Structural Design Loads

The use of composite structures for present and future naval applications represents an important development. Composites offer significant advantages over the traditional metals by virtue of their strength, stiffness and lightweight characteristics. However, the behavior of these composite structures, particularly under highly transient shock loadings, is not that well understood at the present time. Material and structural failure models, for dynamic loading environments are not currently well developed especially for thick, polymer-matrix, fiber-reinforced, composite materials. Moreover, the experimental database for these materials in naval type structures is very sparse.

Figure 28. U. S. Navy triangle for composite applications.

Composite structures represent a significant departure from the traditional ductile, homogeneous, isotropic metal structures. Under severe loadings, metals deform plastically as a consequence of slip along shear lines. Current analysis methods, which are rooted in continuum mechanics, have been developed and applied and these are based upon traditional metallic structures where failures have usually been more global in nature because of the metal ductility.

FRP composites are very heterogeneous materials that combine high-performance fibers in a viscoelastic matrix. There are several levels of heterogeneities to consider: between layers, between the fiber and matrix, and also heterogeneities in the form of voids arising from the processing of the composite. Thus, composites are difficult to characterize and model with the standard ductile material continuum-mechanics approaches.

In addition, composite structures tend to be highly dispersive to propagating waves, and respond non-linearly under severe load because of the development of networks of micro-cracks. As a consequence of all these features, the shock response and evolution of damage in composites are not well-characterized phenomena. Continuum damage mechanics is in general a developing field of research that is not yet mature. Damage theories appear to have progressed further for metal structures because of their more homogeneous, isotropic and ductile nature.

A simple method developed by Dinsenbacher and Sikora has been used for the calculation of the bending moments. This method is based on a curve fit of design bending moments from 13 destroyer and frigate hull forms of U.S. Navy vessels. [Ref 52] It results in standard deviations of hogging and sagging bending moments of +-10% and +-8.5 % respectively. The standard deviation for overall peak-to-peak bending moments is +-4%. The following relationships were used:

$$BM_{hog} = -0.000457 \cdot L^{2.5} \cdot B \quad (1)$$

$$BM_{sag} = 0.000381 \cdot L^{2.5} \cdot B \quad (2)$$

where BM is the bending moment (in lton·ft), L is the length (in ft) and B is the beam (in ft) of the ship. Two major loading cases were examined: a combination of hogging wave and hogging bending moment and a combination of sagging wave and sagging bending moment. [Ref 73]

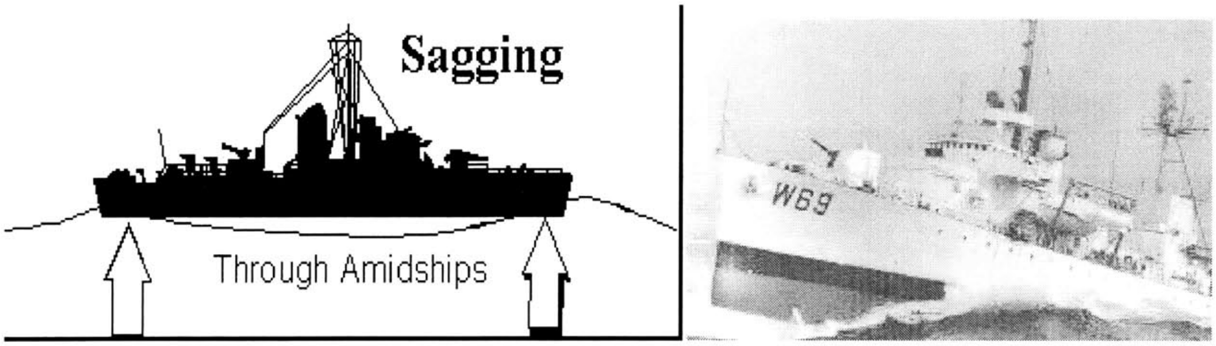


Figure 29. Sagging and Hogging loading conditions

The applied loads were:

- Primary hull loads (Hogging bending moment combined with hogging wave and sagging bending moment combined with sagging wave)

- Secondary deck loads (Hydrostatic pressure of 6m)

- Tertiary deck loads (Live loads of 0.83 m of water height on all decks, Green seas of 1.22 m of water height on the weather deck, Slamming of 2.13 m of water height on the side panels)

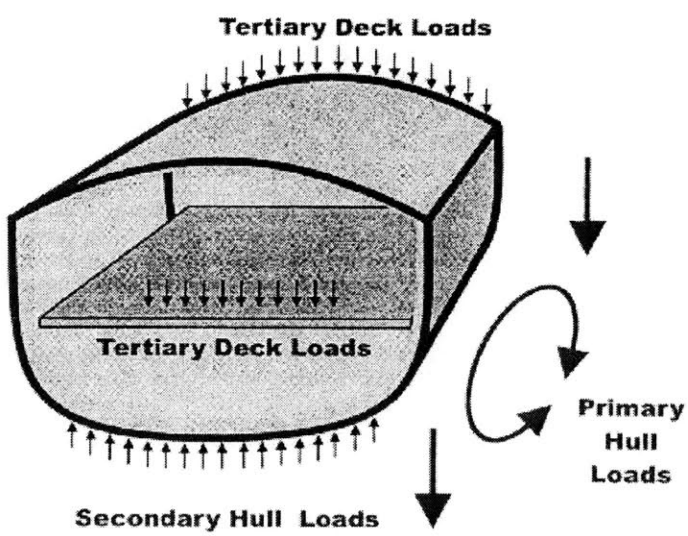


Figure 30. Ship structural loads. [Ref 14]

4.3 Ship Structure Loads

This study necessitated employment of certain assumptions and extrapolations in order to obtain "real life" results. For this study the following assumptions were made:

- Joining, adhesive bonding and assembly were not examined
- Unidirectional plies used for girders, stiffeners and frames
- Balanced symmetric laminates at $[0/\pm45/90]_{symmetric}$ stacking sequence used for plates
- Equivalent properties were considered for plane strain
- Same safety factors used for steel and composite structural concepts

The maximum stress occurs typically at the midship section, in the longitudinal direction. The loads seen by the hull are quantified in terms of static pressures, whereas in practice slamming loading by waves can cause high core shear stresses or high local bending stresses in composites. This is still a gray area in design as insufficient data are available. [Ref 96]

The operational loads on a high-speed vessel may vary considerably in amplitude, but the bottom panels in the slamming area can be subjected to as many as 1 million load cycles to a fairly high level during the lifetime of the vessel which will lead to fatigue if a stress (strain) level that is too high is accepted.

With a load level corresponding to about 30% of the ultimate strength of the material the load can be cycled more than 10^6 times without any risk of fatigue failure. However, during normal conditions of operation the bottom of the vessel will normally only be subjected to about 100,000 cycles at that load-level and the risk of fatigue failure is low for a correctly designed structure. A stress level corresponding to a factor of safety close to 3 for the materials, is also normally the maximum allowed stress level in the composite accepted by the classification societies.

The heterogeneous nature of laminated composite plates and shells gives rise to an exceedingly complex dynamic response in the material. If the wavelength of the loading and the response of the structure is very long compared to the scale of the inhomogeneity, then the material response is governed by effective properties of the equivalent homogenized media. However, if the composite structure is subjected to high rate loads such as shock environments, then the wavelengths of the loading and response of the structure will be much shorter. In this case, the characteristic dimensions of the heterogeneous media become much more important. The interfaces between the material phases cause waves to reflect and refract. Hence, the energy is spread or "dispersed" over many wavelengths.

4.3.1 Types of loading

Besides transient sea-wave loads, naval ship structures must be designed to withstand shock loads from air-blasts and underwater explosions. [Ref 51, Ref 71] The type of loading applied to the material/structural system can be linked to the time duration the forcing function is applied to the material/structure. The loading function may not necessarily be related to mechanical force but can be represented by a ground displacement, velocity shock, impact, or other loading event. In general, the following classes of loads are recognized as generally applied to material/structural systems:

1. static or dead loading

2. quasi-static loads applied during material and structural testing

3. dynamic loads, including

   (a) Vibratory: random, transient, and steady state

   (b) Impact/Impulsive

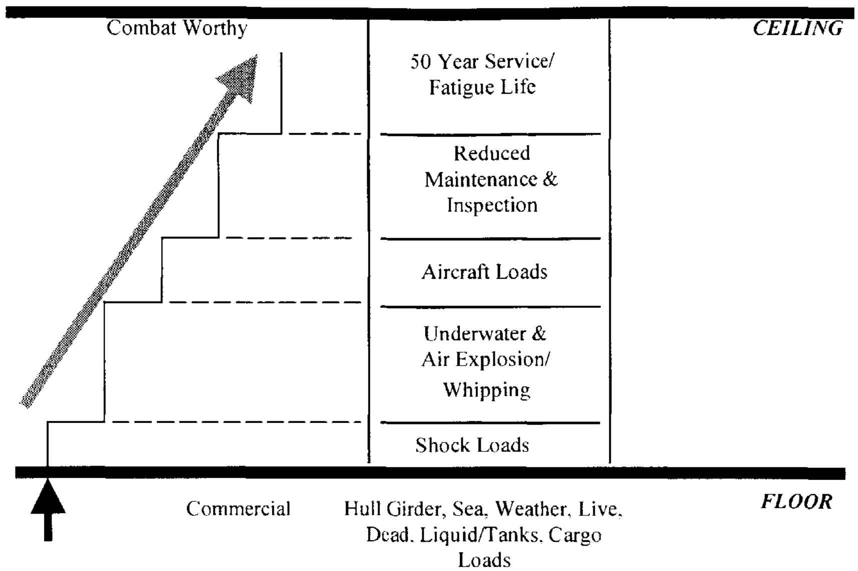


Figure 31. Additional loading conditions that need to be considered for complete structural evaluation.

4.3.1.1 Hydrodynamic loads

In many respects, static and quasi-static loading is linked synonymously with the same testing procedure. Realistically, static refers to very slow, long term load application while quasi-static is usually associated with generating data from laboratory test equipment such as servo-hydraulic and/or screw-driven test equipment. The loading times associated with these tests are considered to be long enough in duration as compared with the material/structural response such that the internal equilibrium within the material/structure is maintained throughout the loading process. As the loading time is shortened, material/structural inertia effects become important and the loading becomes dynamic. Thus, defining the role of the loading type becomes important in determining the material/structural response. The principal types of dynamic loading in which the system responds as a material/structure, and not as a fluid, can be broadly classified as (1) vibratory and (2) impact/impulsive.

For vibratory loading, the type of response obtained is directly linked to the applied force. For example, if the forcing function is repetitive and continuous, then the response can be considered as steady state, that is, to a degree, independent of the exact time of application of the forcing function. Sinusoidal forcing functions are often used for representing this type of vibratory response. When the material/structure response is considered to be transient. Once the transient phase has passed, the material/structural response becomes steady state. The system response in the transient stage, however, may result in higher system stresses and displacements when compared to the response in the time regime following cessation of the load. This result is then of concern to the designer. Random vibration effects occur when the instantaneous magnitude of the load is unspecified for any instant of time and the instantaneous magnitudes are specified by probability distribution functions.

The last class of dynamic loads described is associated with impact/impulse loads. Impact loads are short time loads created by the interaction/collision of two solid bodies, one of which may be at rest. Impulse loads are short time loads produced by striking objects, one of which is not characterized as a solid. For extremely short duration loads, in which the material no longer retains rigidity, the material/structure is said to be exposed to shock loading.

Alternatively to using the load and time of load application as the functional means of classifying the type of loading applied to the material/structure system, the material strain rate can also be considered as a means for identifying the loading type. The linkage between characteristic load times and strain rate effects, as well as methods of loading and dynamic considerations in testing, can be described as shown in the following table:

Table 16. Load Times and Rate Effects.

Constant Load or Stress Machine	Hydraulic or Screw Machine	Pneumatic or Mechanical Machines	Mechanical or explosive Impact	Light-Gas Gun Or Explosive-Driven Plate Impact	Usual Method of Loading
10^{6}-10^{4}	10^{2}-10^{0}	10^{2}	10^{-4}	10^{-6}-10^{-8}	Characteristic time(s)
10^{-8}-10^{-6}	10^{-4}-10^{-2}	10^{0}	10^{2}	10^{4}-10^{6}	Strain rate (s^{-1})
Inertia Forces neglected	Inertia Forces neglected	Inertia Forces important	Inertia Forces important	Inertia Forces important	Dynamic considerations in testing

4.3.1.2 Dynamic Loading Regimes

A useful classification schedule for describing the dynamic response of structural elements related to the dynamic loading regimes discussed is shown in the following table:

Table 17. Structural Response Regimes

Regime	Pulse Duration/Natural Period	Response
1	T/T < ¼	Impact/Impulse
2	1/4 < t/T < 4	Vibratory
3	T/T > 4	Quasi-static

In Table 17 the pulse duration to structure natural period has been used as a guideline to define the system response. For short-time duration pulses relative to the system natural period, the response can be classified as either an impact event or an impulse event with the loading rise time essentially instantaneous. There is a distinction between the two types of events in that impact involves the collision of two solid bodies while an impulsive loading involves interacting objects, one of which is not characterized as a solid. Material response regimes, on the other hand, can be described in terms of characteristic loading times as identified in the following table:

Table 18. Material Response Regimes [Ref 36]

Regime	Pulse Duration/Natural Period	Response
1	10^{6}-10^{4}	Static
2	10^{4}-10^{2}	Quasi-static
3	10^{0}-10^{-6}	Dynamic
4	10^{-6}-10^{-9}	Hydrodynamic

To define the response of material/structural systems to impact events, the forcing function/intensity time history must be quantified. In order to obtain this information, it is necessary to address the collision event of the respective interacting bodies. In many cases of practical importance, one of the bodies is considered to be initially at rest.

4.4 Structural Concepts

Numerous composite shipboard components have been designed to function onboard naval combatants. All composite structure is designed to resist anticipated static and dynamic loads. [Ref 68] Machinery and equipment foundations are another application where composites offer the potential for large reduction in the total outfit weight of a ship. For composite marine vessels four are the candidate structural design concepts [Ref 77]:

1. Monocoque single-skin construction
2. Monocoque sandwich construction
3. Single-skin construction using bulkheads and stringers
4. Sandwich construction using bulkheads and stringers

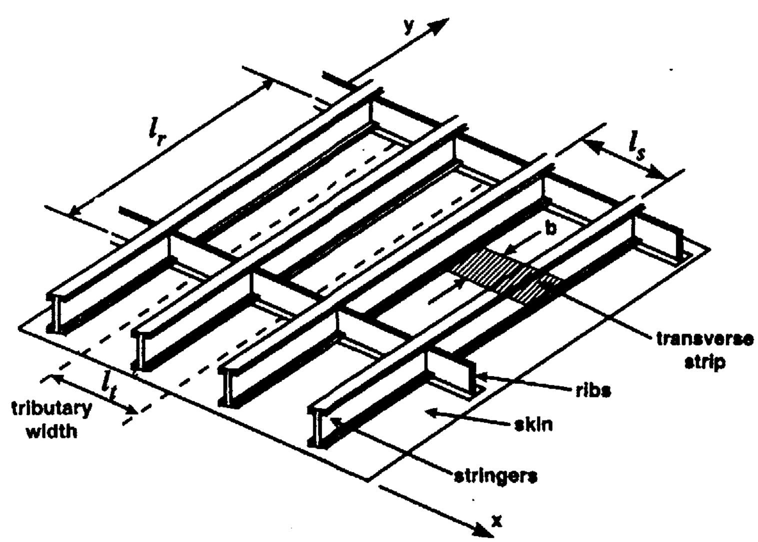


Figure 32. Typical reinforced panel. [Ref 82]

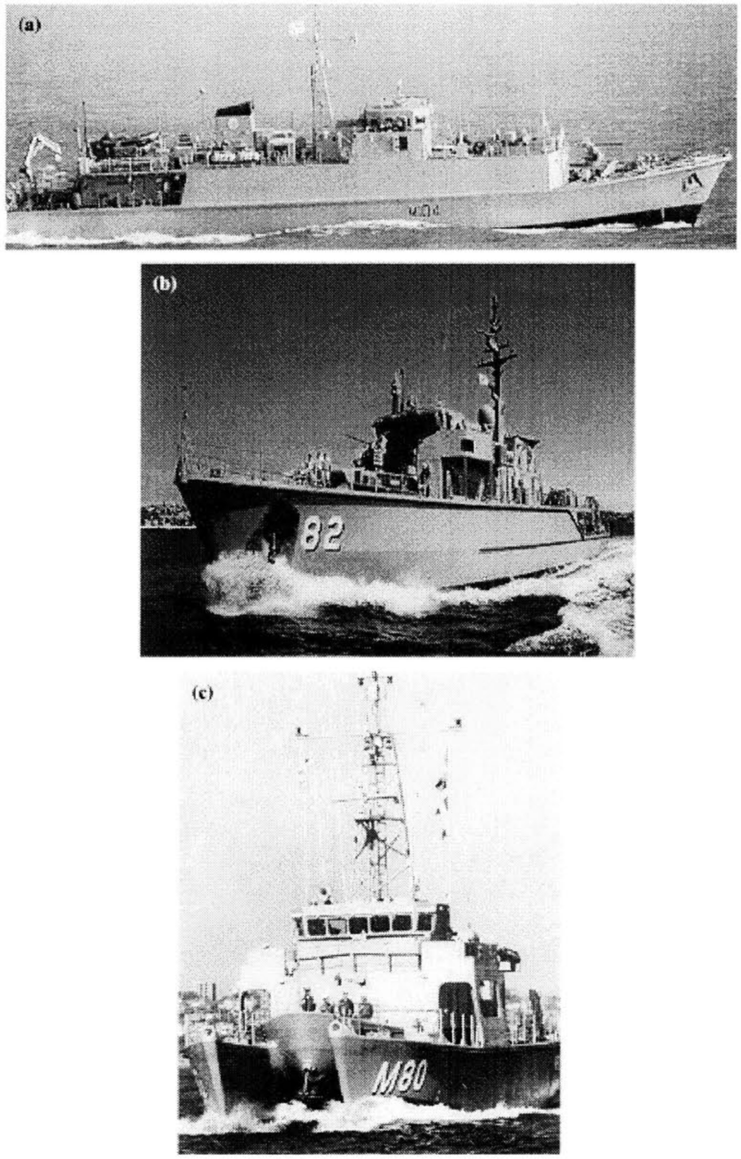


Figure 33. (a) Sandown. (b) Huon and (c) Bay class MCMV that have hull types of single-skin framed, monocoque and sandwich composite, respectively. [Ref 76]

The first type requires very thick skins, which make this method applicable only for small vessels. Sandwich construction requires development of special tools in order to optimize the core material and the structure of the composite layers. Therefore, the single-skin construction, which is a combination of bulkheads and stringers, was selected. This type of concept reduces the effective panel spans and the required strength and stiffness of the composite material used. Figure 34 presents the proposed structural configuration.

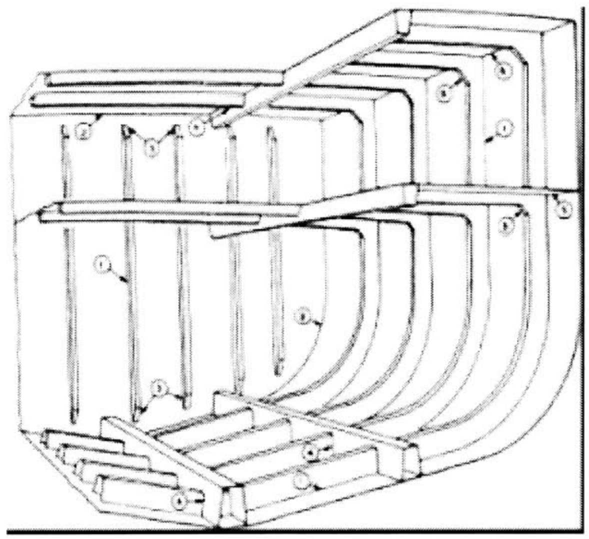


Figure 34. Schematic of the framed single-skin hull design for composite ships. [Ref 77]

The hat cross section was the selection for the stiffeners and girders due to ease of construction and increased bending moment performance of this configuration. In the case of sandwich construction, the possibility of filling the hat section with a light weight core material will enhance the structural performance of the structure.

Figure 35. Types of stiffeners: on the left hand side T-cross section used for the construction of DDG (steel) and on the right hand side Hat-cross section used for the purpose of this study

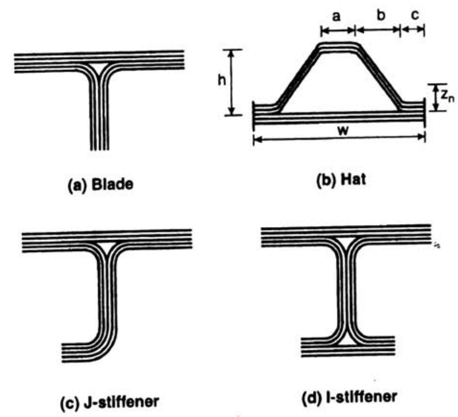


Figure 36. Typical stiffener geometries. [Ref 82]

4.5 Structural Optimization

4.5.1 Design Space

The Design of Experiments (DOE) formalizes and systematizes the design process by defining a design space. Several methods, including Robust Design techniques, allow reduction in the number of variants required to define the design space. In general, well-defined methods exist, such as the Box-Behnken, Central Composite, or Taguchi methods. For this study, Taguchi was selected as the optimization method, due to the fact that requires the minimum amount of experiments compared to the rest of the methods. [Ref 29] Self-converging models allow many variants to be synthesized. Ranges of factors (variables) define the design space. The experimental error is not an issue for this case, because the synthesis models are deterministic. [Ref 28] By using the impact visualization from JMP software, the designer can study the impact of changes in design variables with minimum number of variants.

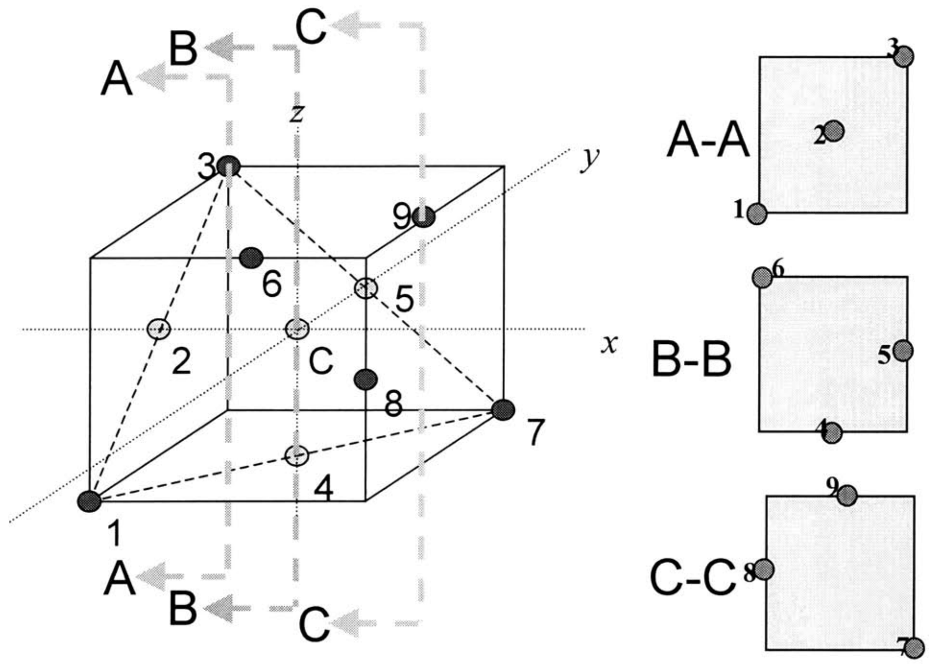


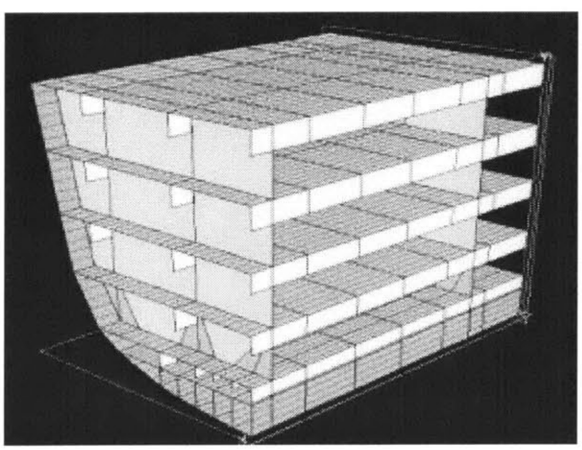
Figure 37. Taguchi design space. [Ref 26]

4.5.2 Formulation of the design problem

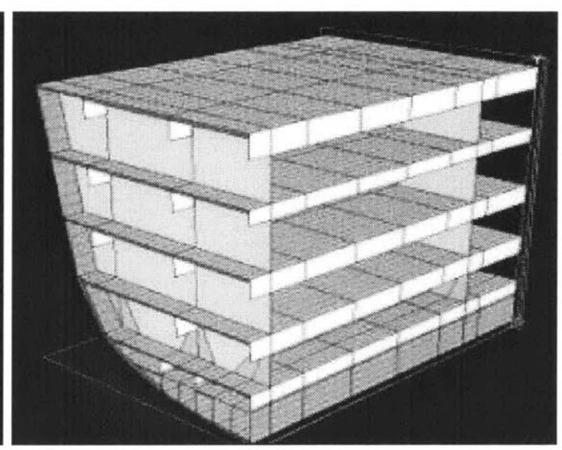
The objective is to develop alternative design concepts that minimize cost and maximize performance of the structure. Typical formulation of a design problem includes a set of constraints and quality criteria or objective (merit) functions that should be maximized or minimized by a proper choice of design variables. In general the design variables directly determine the geometry and the properties of the structure. However, one of the main features of many optimization problems for load-bearing structures is that the design variables do not appear explicitly in the set of constraints, which typically describe the appropriate strength and stiffness requirements for the structure. Instead, such constraints are often written in terms of field variables, i.e., stresses, strains, and displacements which more often than not cannot be written in terms of the design variables (with the exception of a few simple design problems). To overcome this problem, two main approaches are used in optimal design of structures. The first approach is to use the so-called structural optimality criteria methods, which replace the original problem with conditions that are described in terms of the field variables rather than the design variables.

Complicated structures are usually designed on the basis of the second approach, which involves an iterative numerical mathematical optimization process. There exist numerous iterative procedures that search the optimal solution starting from some initial set of design variables. [Ref 40]

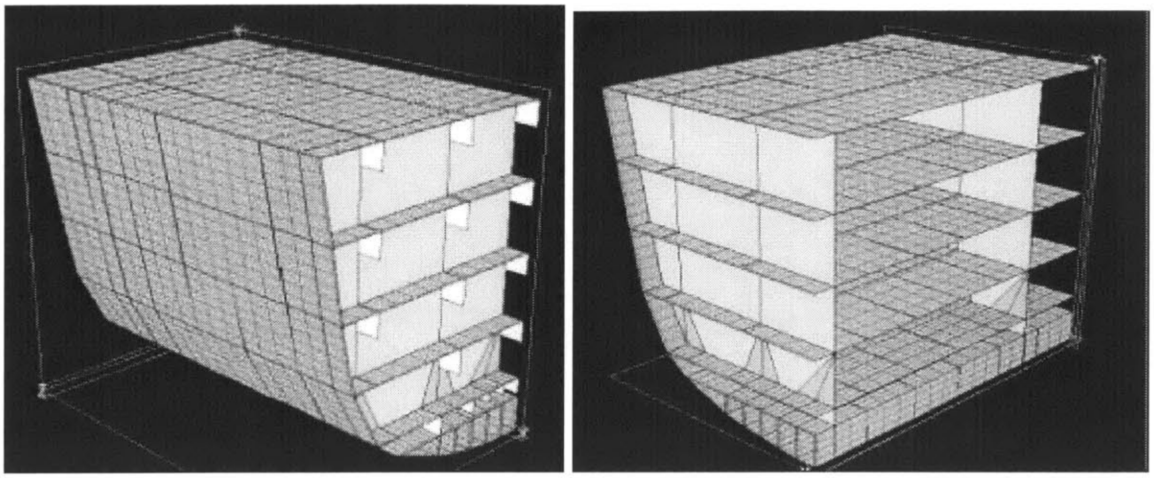
The purpose of this study was to examine the effect of several components on the performance of the structure. Therefore, four different designs were examined. Design A, is similar to the one made of steel, including plates, frames, girders and stiffeners. The only difference except the material (composites instead of steel) was the type of girders and stiffeners used (as described above T-type stiffeners were substituted with hat-cross section ones). Design B is based on design A with the only difference that the frames are eliminated. Design C is similar to design B but is also transversely stiffened. Finally, Design D is based on design C but we eliminated the girders. All four designs were modeled in MAESTRO, a finite element program that offers the structural designer not only the capability of analyzing the structure, but also the capability of optimizing the structural components by using desired dimensions and criteria. [Ref 104]



Design A: Stiffened with hat cross section



Design B: Frame elimination



Design C: Longitudinally (stiffeners & girders) and transversely stiffened (stiffeners)

Design D: Longitudinally and transversely stiffened (stiffeners) without girders

Figure 38. Structural configurations examined using MAESTRO. [Ref 31]

4.5.3 Formulation of the optimization problem

The theory of optimal design deals with the problem of determination of the properties and the shape of a structure to amplify the value of a certain characteristic, called the merit function or the quality criterion, while the values of the rest of its characteristics are constrained to remain within prescribed limits. [Ref 45] Formulation of an optimization problem requires derivation of the governing equations describing the stress-strain state of the structure or the state variables, and formulation of constraints imposed on the state and design variables, and the quality criterion. The problems of optimal design are usually formulated and solved on the basis of two main approaches—continuum and discrete. The continuum approach implies the representation of the state variables, i.e., stresses, strains, and displacements, and the design variables as continuous functions of space coordinates. The discrete approach is based on the idea of discretization of the structure to represent it as a system of a finite number of interacting elements. [Ref 1]

In order to define the design space for each structural design we had to specify the factors and levels, which will then provide the optimum solution. The design space is defined by ranges of factors (variables). In this case these are the following:

- *Design A: Plates, Frames, Girders, Stiffeners*
- *Design B, C: Plates, Girders, Stiffeners*
- *Design D: Plates, Stiffeners*

Then we set the variables to a number of levels, which are the following:

- *Carbon/Vinyl Ester, Glass/Epoxy, Glass/Vinyl Ester*

The total number of variants needed for an experiment is:

$(\text{number of factors})^{(\text{number of levels})}$

For a full factorial design we need the following number of experiments: Design A needs 64 experiments, Designs B and C need 27 experiments, and, Design D needs 9 experiments. Using Taguchi methods for optimization we need only 9 experiments for each design in order to define the design space and select the optimum design. [Ref 27]

4.5.4 Optimal Design

Optimal structural design can be referred to as one of the most important and promising branches of applied mathematics and mechanics. The basic problem of optimal design is to construct a structure that satisfies a system of given constraints and provides the best quality and performance. Although this problem is quite natural and has been known for a long time, development of a consistent theory of optimal design has matured only recently. This delay is associated with three reasons. First, the most important application of optimal design comes from such modern fields of industry as the aerospace engineering. Second, actual problems of optimal design for complicated spatial structures can be efficiently solved only with the aid of modern analytical and numerical methods of applied mathematics and mechanics. And third, realization of optimal structures has become possible only with development of sophisticated manufacturing processes and computer-controlled machines. Another important contribution to the theory and application of optimal structural design is associated with the maturity of modern composite material technology. [Ref 1]

Composite structures, as a rule, can efficiently work only having the optimal shape and material distribution corresponding to specified loading and operational conditions. Because of possible applications that allow us to modify existing structures and develop novel structural concepts with improved performance, optimal structural design is currently under intensive study in many countries.

Optimal design implies determination of the values of design parameters that control shape, material properties, and dimensions of a structure, which must meet a set of specified constraints and improve some measure of quality to achieve the best possible design. In general, optimal design is a natural part of the activities of any design engineer whose challenge is to develop a proper structure saving as many resources (material, energy, labor, etc.) as possible.

Usually, there exists an infinite set of structures that satisfy a specified set of design requirements. Therefore, the problem of design should be formulated to find the best one through the use of the methods of optimization. The objective function for such problems is usually the cost of the mass of the structure, while design variables (or so-called control functions) that should be determined are associated with material distribution through the laminate thickness, as well as the number of layers. Constraints are usually imposed on the physical variables (or so-called phase functions) which should satisfy the governing ordinary differential equations and the associated boundary conditions of the boundary value problem which is used to model the physical process of wave, material or signal propagation through the laminate thickness.

The selection of the optimal design is related to the designer's preferences. Three cases were examined in this study. The first one was the selection of the optimal design based on the weight minimization, the second one was based on the minimization of cost and the third one was a combination of the first two with a relative relationship of 50-50%. Moreover, we tried to minimize the objective function:

Objective Function= (0.5· weight) + (0.5· cost)

For the cost of this application we used the following relationships in order to calculate the total cost (TC) [Ref 22]:

$$AC = \frac{SLR}{AE} \quad \text{and} \quad TC = AC + RC$$

where, AC is the application cost, SLR is the standardized labor rate (approximately $50/hour), AE is the application efficiency and RC is the raw cost. Table 19 presents the results for each matrix used.

Table 19. Cost associated for the application of composite materials. [Ref 74]

Material	Raw Cost ($/kg)	Application Efficiency (kg/hr)	Application Cost ($/kg)	Total Cost ($/kg)
Graphite / Epoxy	43.60	2.72	18.4	62.00
Graphite / Vinyl Ester	43.60	3.60	13.8	57.40
Glass / Epoxy	24.30	5.30	9.4	33.70
Glass / Vinyl Ester	24.30	7.25	6.91	31.20

The comparison among the optimum designs A, B, C and D was based on the following criteria, which represent the major advantages of the application of composites in marine structures and at the same time provide a safe and efficient structure [Ref 20]:

- Weight reduction more than 40%
- Maximum deflection: less than 20 times of steel one
- Cost and manufacturing complexity

4.6 Design Results

Table 20 presents the results for the optimum designs A to D for each different minimization (weight, cost or objective function).

Table 20. Design results for each structural configuration (matrix composition and associated value)

Optimum Design	min Weight		min Cost		min Obj. Function	
	matrix	kg	matrix	$M	matrix	value
A						
Plate	C/VE		GL/VE		GL/VE	
Frame	C/VE	**63216**	GL/EP	**2.71**	GL/EP	**0.89**
Girder	C/VE		GL/VE		GL/VE	
Stiffener	C/VE		C/VE		C/VE	
B						
Plate	C/VE		GL/VE		C/VE	
Girder	C/VE	**46954**	GL/VE	**2.43**	GL/VE	**0.95**
Stiffener	GL/EP		C/VE		C/VE	
C						
Plate	C/VE		GL/VE		GL/VE	
Girder	C/VE	**56812**	C/VE	**2.68**	GL/VE	**0.89**
Stiffener	C/VE		GL/EP		GL/EP	
D						
Plate	C/VE	**49452**	GL/VE	**2.34**	GL/VE	**0.85**
Stiffener	C/VE		GL/VE		GL/VE	

Figures 39 and 40 present the values for the maximum deflections of each design. It can be seen that designs B and D present deflections that are approximately 40 times bigger than the steel one.

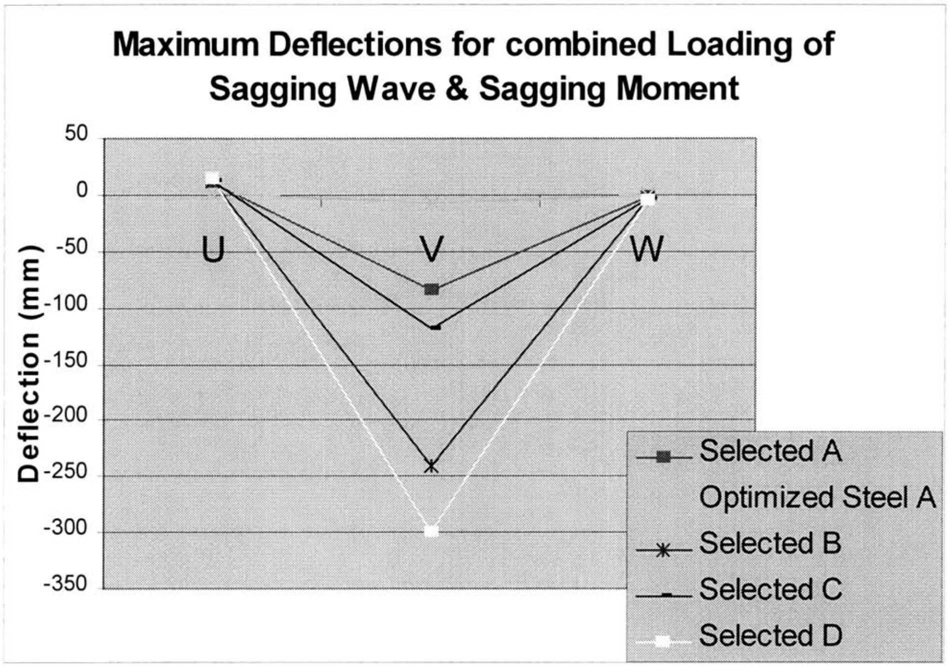


Figure 39. Maximum deflections for sagging conditions.

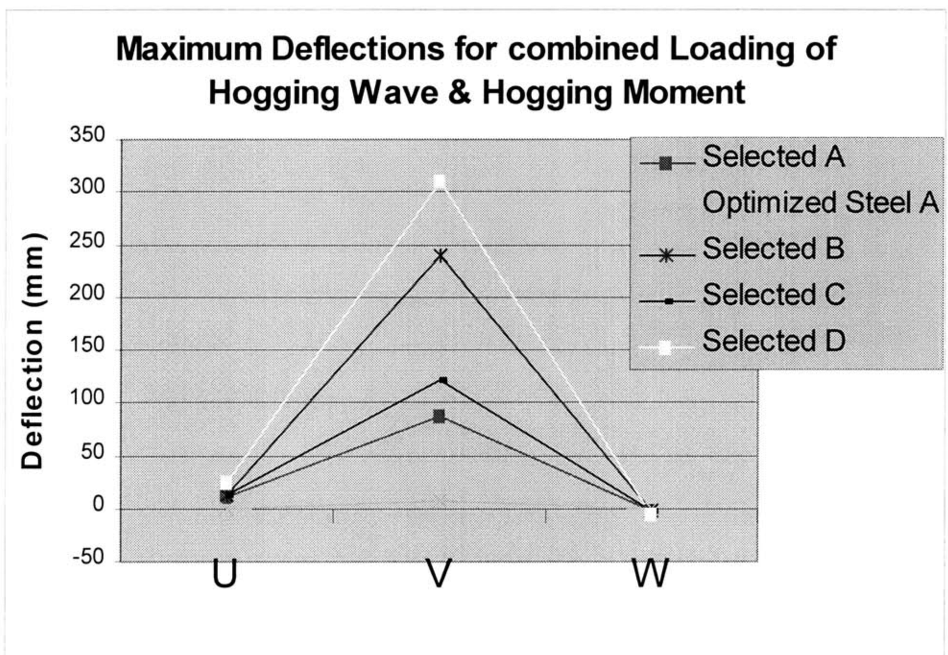


Figure 40. Maximum deflections for hogging conditions.

Based on a U.S. Navy study ships from composites with structural envelope stiffness of 25% or more of the steel baseline would have adequate stiffness for alignment of distributed systems. [Ref 70] Using the criteria described above, Design C is the one that meets all of them, while Designs B and D fail to meet the second criterion and Design A fails to meet the last criterion. Table 21 presents the final results and provides a comparison between the initial steel baseline hull and the selected Design C.

Table 21. Characteristics of Steel Baseline Hull vs. Selected Design

Characteristics	**Steel Baseline Hull**	**Design C**
Structural Configuration	Stiffeners, frames, girders	frameless-longitudinally & transversely stiffened (stiffeners & girders)
Weight (Kg)	267610	56812
Cost ($M)	2.22	2.99
Max. Deflection (mm)	6.85	121.92
Max. Plate Thickness (mm)	32	35.1
Materials	Steel	Carbon/Vinyl Ester

Concerning the results for the stress distribution for the selected design C, we can observe from Figures 41 and 42 that the highest values for the stress at each different structural component do not exceed the maximum, which could lead to the failure of the structure.

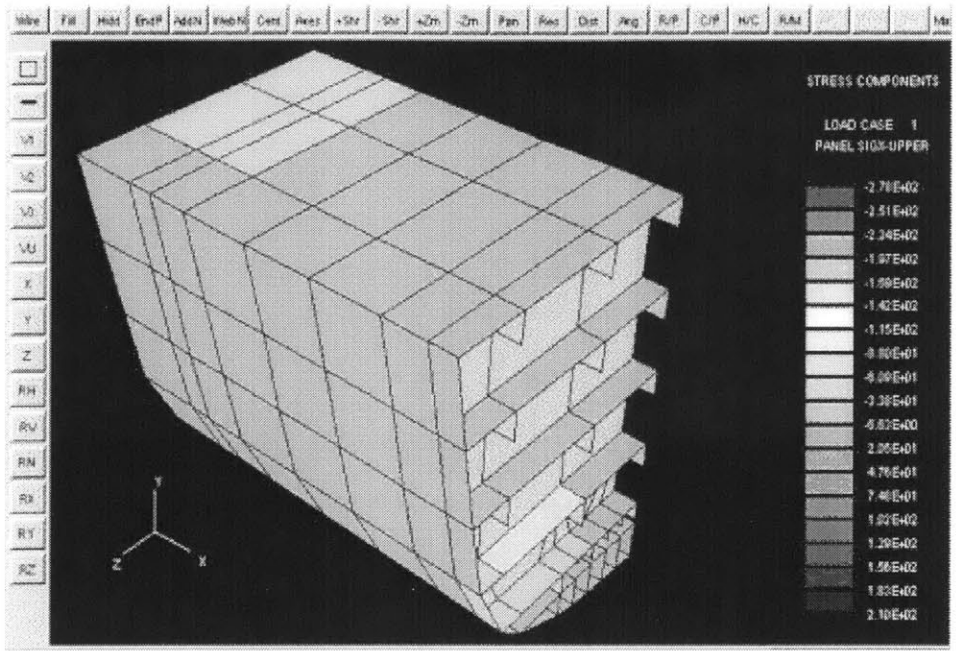


Figure 41. Load case No 1. [Ref 31]

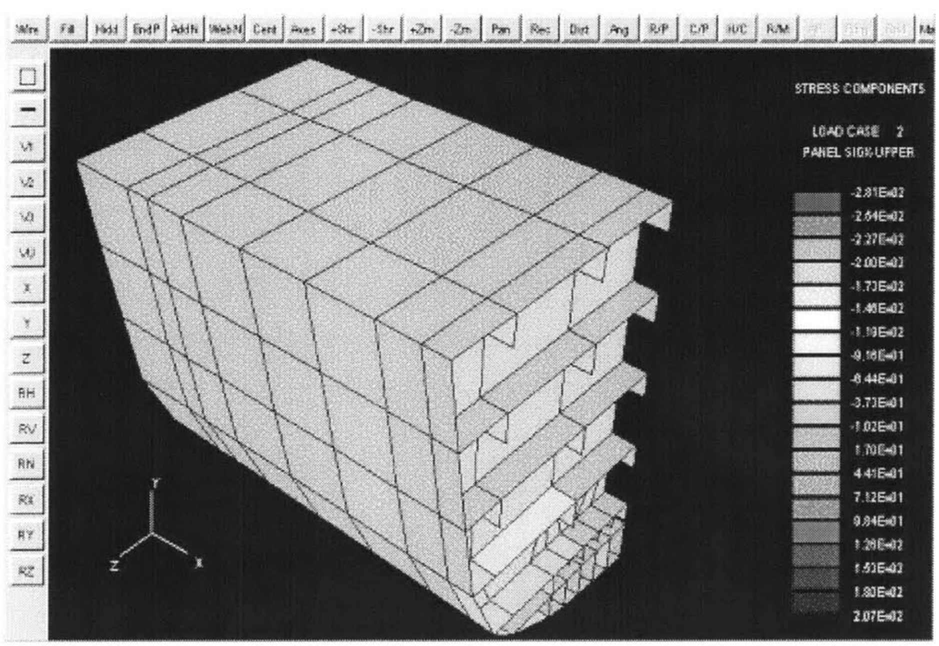


Figure 42. Load case No 2. [Ref 31]

MAESTRO provides as an output, limiting values for the partial safety factors at each panel, called adequacy parameters. This result offers the designer the opportunity to specify where the structure faces an extreme case and especially for which type of failure. Figures 43 and 44 present these values for the two major loading cases examined.

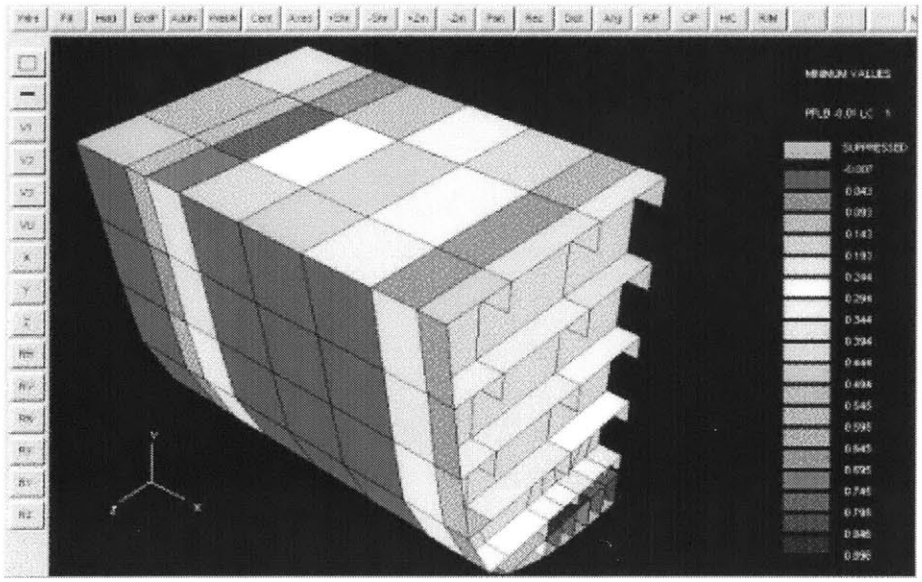


Figure 43. Adequacy parameters for Load case No 1. [Ref 31]

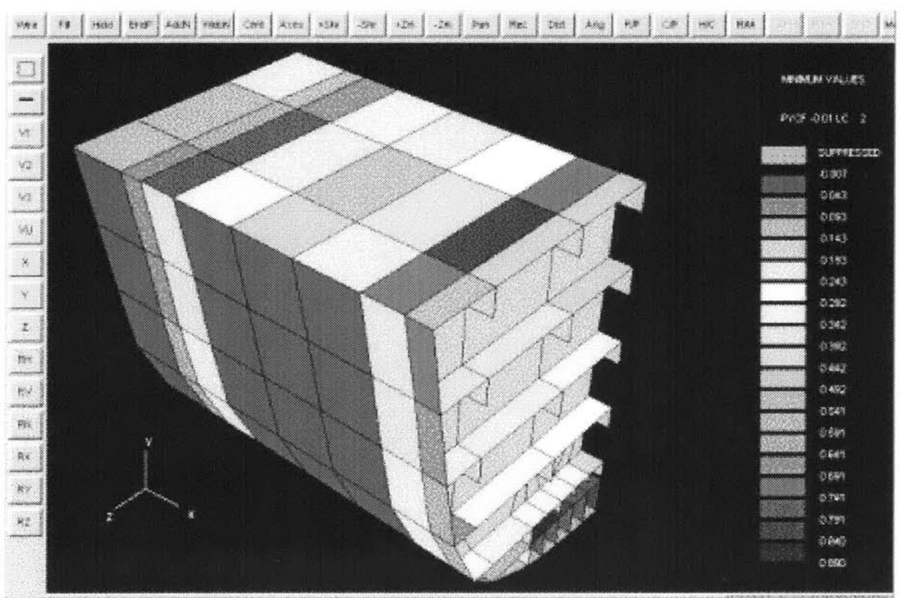


Figure 44. Adequacy parameters for Load case No 2. [Ref 31]

4.7 Safety Factor Sensitivity Analysis

Recognizing that design loads did not represent maximum lifetime loads, and that stress analysis did not represent the actual effects of those standardized loads, factors of safety are developed to link the two. In some cases, the factor of safety has its own assumptions of load combinations built in, such as the relationship between primary axial and secondary bending stress in a plate-stiffener combination.

In the absence of construction specifications and design procedures, and the need to reduce fabrication and ownership costs while incorporating new shipbuilding practices, a tool to assess risk is required. Therefore, a safety factor sensitivity analysis was performed to present the differences of using specific criteria that are dependent to the designer's desires since no specific ones exist for this type of application. Table 22 presents the results in weight and cost for different safety factors, ranging from 1.25 to 3.0.

Table 22. Safety factor sensitivity analysis.

Safety Factor		Weight (Ltons)	Cost ($M)
Collapse: Serviceability:	1.50 1.25	0.57	2.99
Collapse: Serviceability:	2.00 1.75	0.78	3.35
Collapse: Serviceability:	2.50 2.25	0.92	4.52
Collapse: Serviceability:	3.00 2.75	1.15	5.67

The application of glass-fiber reinforced polymer (GRP) to naval and other vessels has often been accompanied by the application of conservative design safety factors due to limited durability data and to account for underwater shock loading. Increasingly GRP is being proposed and tested for critical marine components such as masts, submarine control surfaces, transmission shafts and propellers. This follows the application of GRP to ship primary structures including hull, decks and structural bulkheads, and also to superstructure, framing members, non-structural bulkheads, submarine casings, sonar domes and radomes. A design, which seeks weight efficiency or component geometric efficiency, may seek to minimize design safety factors for which ageing should remain a consideration.

Composite structures differ significantly from metal structures in their response to loading environments. Composite plates and shells are typically thicker than comparable metal structures. Couple this with the lower compliances of their matrix components, and fiber reinforced composites typically display much more transverse shear effects in general.

Fiber reinforced composite laminates are also more heterogeneous and anisotropic than typical structural metals. The layering of various ply combinations produces a complex arrangement that can only be approximated in an average sense. Without a homogenization procedure, one is forced to attempt a detailed modeling through the thickness direction of the plate or shell structure using solid elements. This is typically unfeasible given the thickness to length ratios of practical plate/shell structures, which would require large number of solid elements.

Through thickness damage (microcracks or delaminations), especially in dynamic loading environments, is much more of a concern in composite structures than it is in metal structures. This type of damage is also difficult to model accurately. The standard displacement finite element codes that are popular today do not contain plate or shell elements which can account for through thickness (normal direction) deformation and stress even in a crude fashion.

To account for through thickness effects using the currently available commercial finite element method (FEM) technology one often has no other choice but to use solid elements – thus producing very large models to be solved.

5 Cost Analysis

The worldwide FRP market continues to gain momentum. With an average annual growth rate of nearly 6% over the last five years (1996 to 2001), the trend is expected to hold steadily in most sectors throughout 2002. Because composite materials encompass a wide variety of material combinations that can be specifically tailored for diverse end-use applications, FRP is increasingly used as a substitute for, or improvement upon, traditional materials.

Cost effectiveness in composites is being accomplished by automated manufacturing technologies, improved material systems, and concurrent design methodologies. As commercial enterprises are becoming the major innovators and pioneers in the use of advanced composites, greater emphasis is now being placed on cost-effectiveness. From the magnitude of cost savings that can be achieved throughout the product cycle up to production, it is important to notice that although only a small fraction of program costs have been deployed at the early design stages, the decisions made then could influence up to 94% of the total cost.[8] This leads to the notion that some of the best opportunities for cost reduction arise at the design stage of product development.

5.1 Market Analysis

The advanced composites industry has entered a phase of slow but steady growth. While not booming, the market is moving forward, driven in part by healthy commercial aircraft orders and growing composites demand in Asia and Europe. Growth of composites in commercial applications continues to look promising, in automotive, infrastructure and offshore oil markets,

---

[8] Noton, B., "Cost Drivers in Design and Manufacture of Composite Structures.. In Reinhart, T. (ed.)

Composites: Engineered Materials Handbook, ASM, 1989.

as cost pressures force fiber prices down. As the plastics industry as a whole evolves at a pace much faster than the metals industry, composite hull technology is also evolving at a rapid pace.

The trend toward consolidation, acquisitions, mergers and changes among end users as well as materials suppliers has continued to occur with an eye toward diversification into potentially huge, emerging applications. This direction will lead to the reduction of the costs associated with the production of composite materials and composite structures.

In response to ever-growing pressure to produce parts for less, without sacrificing quality, companies continue to pursue cost reductions through more efficient composite manufacturing techniques. For example, automated tape lay-up methods are being used more frequently, reducing the traditionally high costs of hand lay-up. Resin transfer molding (RTM) and resin infusion processes both are examples of low-cost approaches to fabricating. The new markets that are poised to expand will take advantage of the superior performance qualities advanced composites can offer. As performance is proven, and industry become more established, applications using high-end fiber-reinforced materials will continue to grow in acceptance.

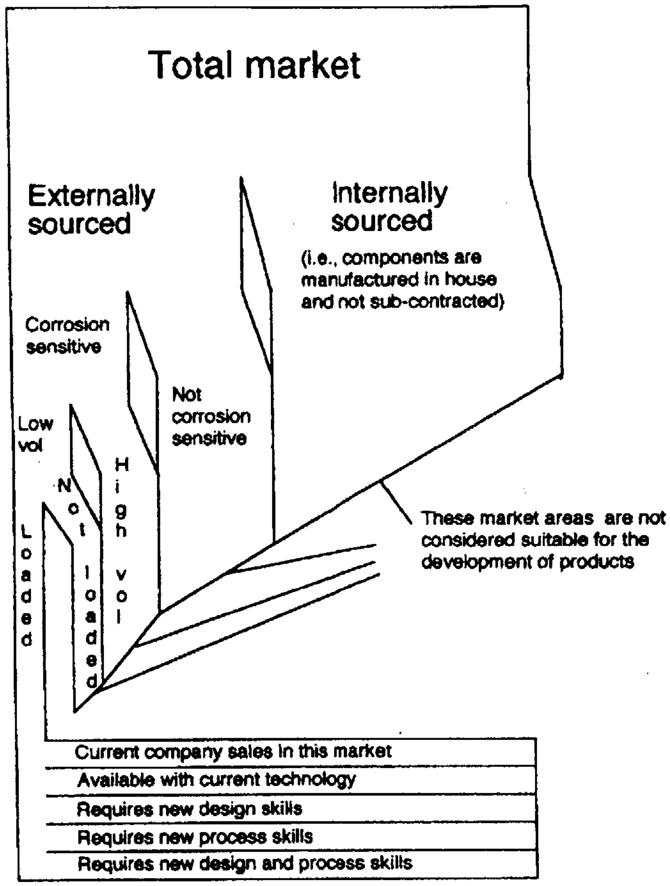


Figure 45. Example of market breakdown. [Ref 80]

High strength and light weight remain the wining combination that propels composite materials into arenas, but other properties are also gaining recognition. Composite materials offer good vibrational damping and low coefficient of thermal expansion (CTE), characteristics that can be engineered for specialized applications. High-performance composite materials reduce fatigue and provide design/fabrication flexibility that can significantly decrease the number of parts needed for specific applications, which translates into less raw material, fewer fasteners and joints and less assembly time. [Ref 88]

Another characteristic of composites is proven resistance to temperature extremes, corrosion and wear, especially in industrial settings. This characteristic can lead to lower product lifecycle costs. Standardization of repair materials and procedures will reduce repair materials inventory and cost, ensure consistent quality, as well as reduce high cost of qualifying and testing materials for particular programs.

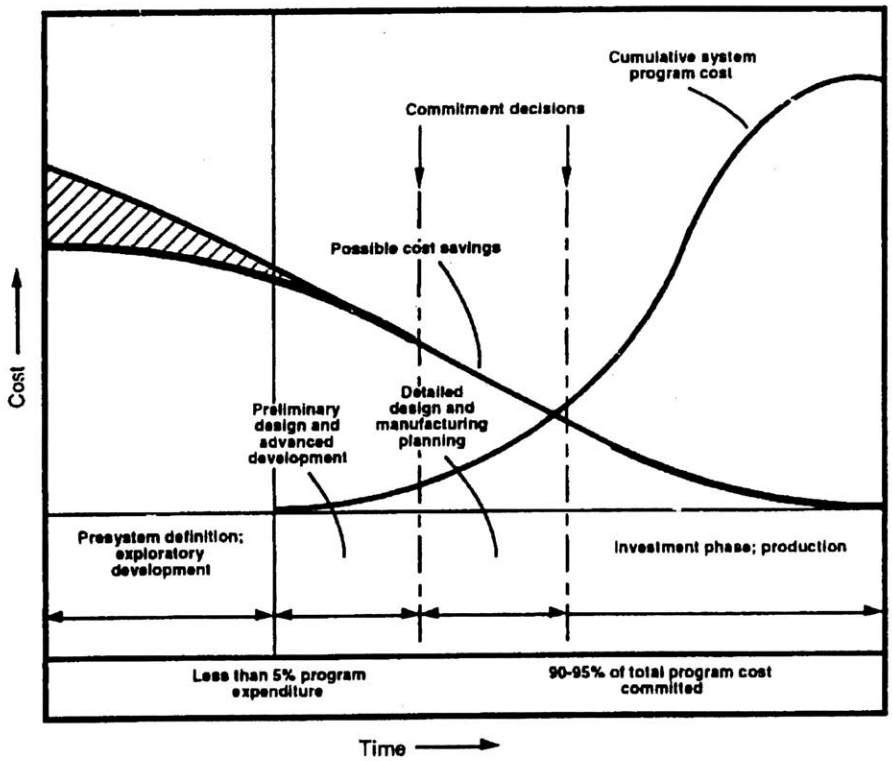


Figure 46. Program phase breakdown in steps concerning cost and time issues.

Acceptance of composites in construction has been helped by development of codes and design standards, a process that is slowly but surely coming to the fore. Composites continue to gain wider acceptance in the marine market. With billions of dollars annually projected to be spent in infrastructure and construction projects, new building specifications that address significant composite material differences and propose design parameters to encompass liability concerns are critical to the success of their end use. Governments and engineering associations worldwide are cooperating to standardize workable international design parameters, and the composites industry is forging critical associations with the marine engineering community.

Growth continued in the global composites market in 2000 at a rate of about 4 percent in North America and nearly 6 percent worldwide. The composites industry outlook remains healthy, particularly in Europe where strong demand is creating a tight fiberglass market. According to figures compiled by the Freedonia Group Inc. (Cleveland, Ohio)[9], U.S. reinforced plastics demand will increase at an annual rate of 3 percent to 4.2 billion lbs by the year 2005, creating a market for 2.9 billion lbs of resin and 1.3 billion lbs of reinforcements. While thermosets resins will remain dominant and will account for over 60 percent of demand through 2005, Freedonia predicts faster growth of thermoplastics for a diverse range of applications, because of cost and performance advantages. The composites industry grew at double digit rates in Europe and Latin America in 2000, putting the squeeze on glass reinforcement supply. But, increased fiberglass capacity continues to come on line in China and other countries, to meet demand. According to the Composites Fabricators Association (CFA), thermosetting polyester resin sales in the U.S. and Canada were up 4.8 percent for 2000 as compared to 1999 figures, thanks to marine and transportation markets.[10]

5.2 Supply and Demand

The cost of using advanced composite materials has come down as repeatable, high-volume manufacturing methods have come of age. Aerospace and high-volume sporting goods have utilized the majority of prepegs made with standard/intermediate tensile modulus, and small-tow (1K to 12K) carbon fiber; significant growth in these applications created a small-tow shortage in 1996 and 1997. However, the market is currently saturated. The oversupply is coupled with pressure on fiber producers and prepreggers by customers to bring prices down. With the Suppliers of Advanced Composite Materials Association (SACMA) now defunct, carbon fiber supply and demand data are scarce. Although there is likely some debate over the statistics, an estimate of overall worldwide demand for continuous carbon fiber was around 30 million lbs in 2000.

---

[9] Study obtained from www.freedoniagroup.com

[10] Composites Technology, June 2001, International edition.

Industry suppliers are forecasting that demand should increase about 2 million lbs per year -or about 6 percent- over the next several years. But, this compares to an industry capacity of nearly 46 million lbs in 2000 for conventional and large tows. While increasing demand will gradually shrink the supply/demand overcapacity, there will continue to be a plentiful carbon fiber supply for a foreseeable future. Carbon suppliers are in the process of forming a new consortium that will track fiber statistics and industry trends. [Ref 35]

In contrast to carbon, the supply of glass may be tightening with few new furnaces coming online and demand growing. A glass shortage will certainly create opportunities for alternative fibers to gain a greater market share.

Despite the fact that "promising" market applications is always on the horizon but never quite within reach, the overall outlook for the composites industry bodes well. Current fiber capacity will facilitate entry into markets as they develop. Lessons learned during the past decade require suppliers, fabricators and customers to continue operating at lean levels. Key efforts to achieve industry objectives include increased automation and development of innovative manufacturing processes, integrated product teams and design standardization.

The worldwide demand for faster and increased payload military and commercial vessels over the last 5-10 years has heightened the interest in composite materials within the marine industry. In the same timescale, composite materials and low cost fabrication processes available to shipbuilders have also evolved considerably.

5.3 The Challenges Facing Industry

The past ten years have brought with them the greatest challenges to business. Customers demand more and expect to pay less for it. Global competition, mass customization, and low unemployment have forced us all into situations that were unthinkable only a few years ago. Engineering, research, and development budgets get slashed as profit margins drop. Sales and Marketing say that customers want lighter, long-lasting, more stylish designs with more variety. The company thinks that composites may be the answer, but how do you get that kind of expertise without years of development and a government sized budget?

Most steel used in merchant shipbuilding is low carbon, mild, or ordinary-strength steel. Higher carbon and other alloy steels are also used. These steels are used because of improved properties compared to mild steel, such as greater strength, better corrosion resistance, and higher notch toughness. The properties of these various grades of steel are obtained through variation in the composition of the steel and in the manufacturing processes. Structural steels used for commercial construction in the United States are certified by the American Bureau of Shipping (ABS). [Ref 8]

The major considerations in the choice of steels for shipbuilding are properties of the steel, ease of use in construction, availability, and cost. Mild steel is predominant in commercial shipbuilding because of its relatively low cost, ready availability, and ease of welding. The higher-strength steels find considerable application in naval ship construction due to design constraints, especially the need to control weight without reducing strength. [Ref 46]

5.4 Material Costs

Depending on type, between 40 and 70 percent of the total cost of a ship is material and subcontracted services. The material market parallels the labor market, in that it is heavily influenced by the characteristics of the product market. However, in the short run, price and availability of material are more responsive to the effects of the economic activity in other industries. This is due, in part, to the relatively small shipbuilding market in the United States, compared to the overall industrial base. Manufacturing lead times, another measure of the performance of the supplier base, have also generally exhibited the expected response to economic conditions. Thus lead times will also be influenced more by general economic conditions than by the status of the shipbuilding industry. [Ref 8]

The shipbuilding supplier base, along with other predominantly defense-oriented industries, has declined since the 1950s. The US industry is, in several instances, dependent on a single supplier. Examples include suppliers of anchors, anchor chain, and activated rudders.

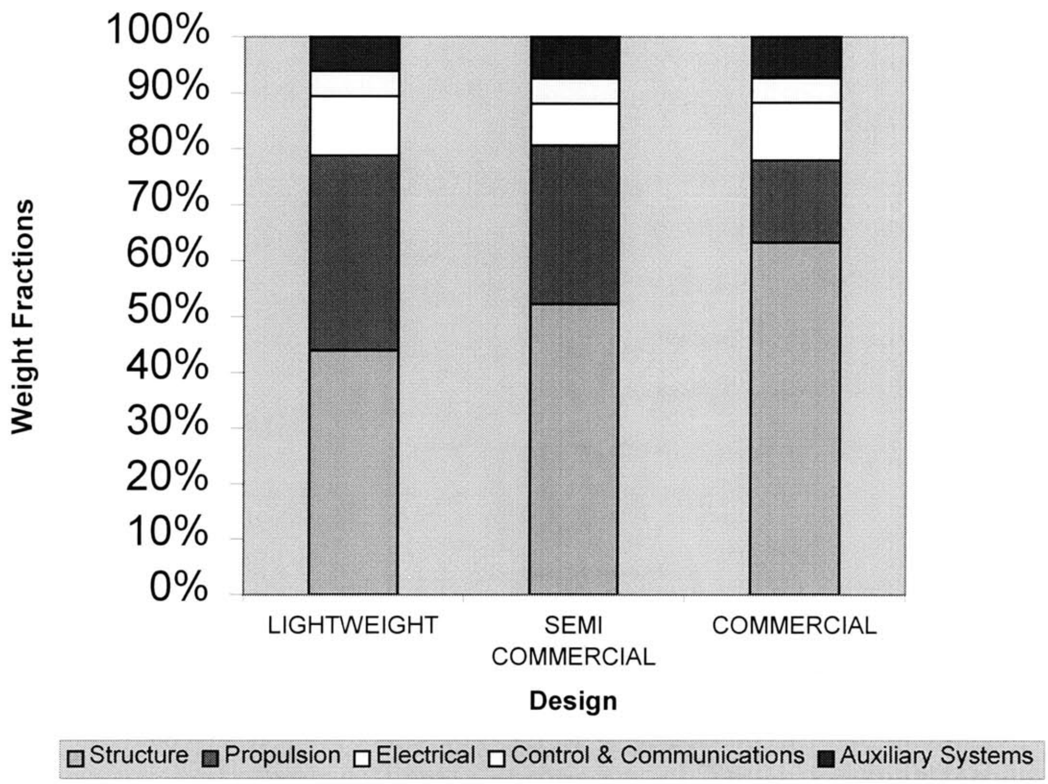


Figure 47. Structural Weight Fraction Comparison for a Corvette Design. [Ref 47]

The cost competitiveness of composites depends on how important the weight reduction or environmental resistance provided by the composite is to the overall function of the particular application. Although glass fibers are typically lower in cost than aluminum on a weight basis, carbon fibers are still higher in material cost. Equally or more important than the material cost is the cost of manufacturing. In some cases, composite structures can achieve significant cost savings in manufacturing, often by reducing the number of parts involved in a complex assembly. There is a large variability in cost and labor content between the various methods of composite manufacture, and much attention is currently being given to reducing manufacturing costs.

Table 23: Reinforcement fiber properties and cost[11]

Fiber	Tensile Strength psi X 10^3	Tensile Modulus psi X 10^3	Ultimate Enlogation	Cost U.S.$/lb
E-glass	500	10.5	4.8%	0.92 to 2.00
S-glass	665	12.6	5.7%	6-10
Kevlar®	525	18	2.9%	14-20
Carbon	350-700	33-57	0.38-2.0%	8-30

5.5 Complexity

It has been established that the complexity of a part is a significant cost driver in parts manufacture. A cost model for composites manufacture should therefore incorporate measures of complexity that a designer can easily abstract from a design with readily available design tools. The complexity metrics should also conform to the cost structure having some physical significance.

Burnet suggests the need to develop complexity measures, which can be used as bases and guidelines for cost estimating methodologies.[12] Burnet stipulated that part complexity could be categorized into three different types:

- Complexity of concentration
- Complexity of distribution

[11] Cost varies according to the style of fabric supplied.

[12] Burnet, C., "Cost Estimating: the Science of the Possible", Forecasting Costs for the 21st Century, Proceedings of the Royal Aeronautical Society, November 1986.

- Complexity of state

The complexity of concentration is an indicator of the concentration of parts or features within a certain space. Conversely, the complexity of distribution relates to the intricacies encountered with widely distributed systems. The complexity of state is associated with the difficulties that arise with specific materials or manufacturing processes and environments.

5.6 Economical Effects

Competitive means low cost. It is usually difficult to obtain productivity and construction cost data for marine composite structures. Data is very dependent upon the geometric complexity and material selection, along with the quality a fabrication process can deliver. Polymer composite materials are more expensive than other traditional structural materials on a weight basis. Good design and manufacturing techniques can reduce part of the cost differential between polymer composites and traditional structural materials. Life-cycle costing can help polymer composites overcome the remaining cost differential with traditional structural materials by considering the lower maintenance and demolition costs as well as the lower indirect costs.

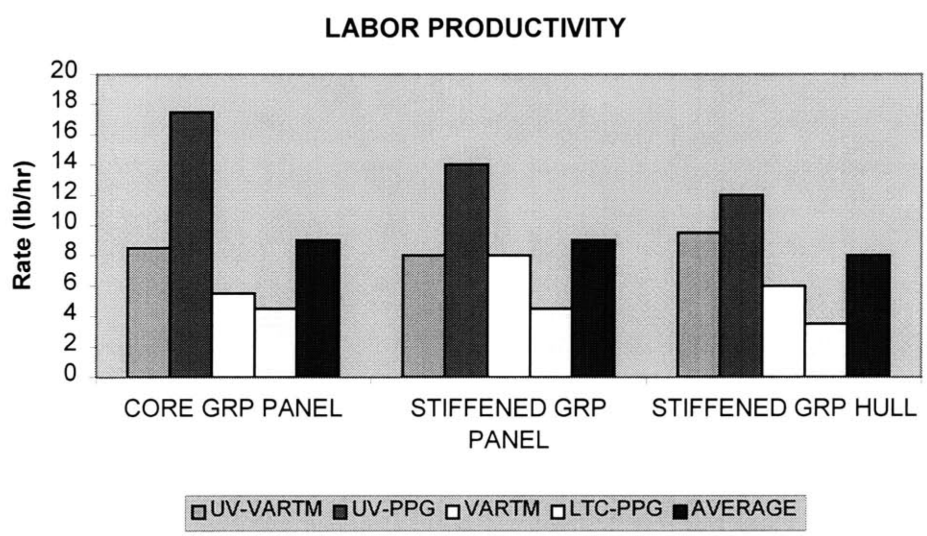


Figure 48. Productivity Rate for Different Types of FRP Ship Structures. [Ref 47]

There is a large cost differential in the raw material costs and the high manufacturing costs. The two primary approaches to reduce this significant cost differential are (I) Life-Cycle Cost and (II) Polymer Composite Cost Reduction. Significant cost reductions can occur with large orders which would reduce the high unit set-up and tooling costs and new designs and bulk material purchasing which would lower unit material costs and require less materials. Higher line speeds and wider sections would also help reduce costs.

However, even with all these manufacturing and material cost reductions, the cost of the polymer composite structure may still tend to exceed that of the traditional steel structure. The life cycle cost advantages of the polymer composite structure must be included to offset the lower initial costs of the traditional steel structure. The minimization of the total project life-cycle cost does not minimize the life-cycle costs of each participant. Trade-offs can be made among factors that affect the life-cycle costs, such as the relationships between initial construction costs and future costs of maintenance, repair, rehabilitation and disposal (MRD).

The objective of this approach is to demonstrate the widespread applicability of composite materials technology as an economical means of manufacturing structural components, and especially the hull of a vessel, for marine structures.

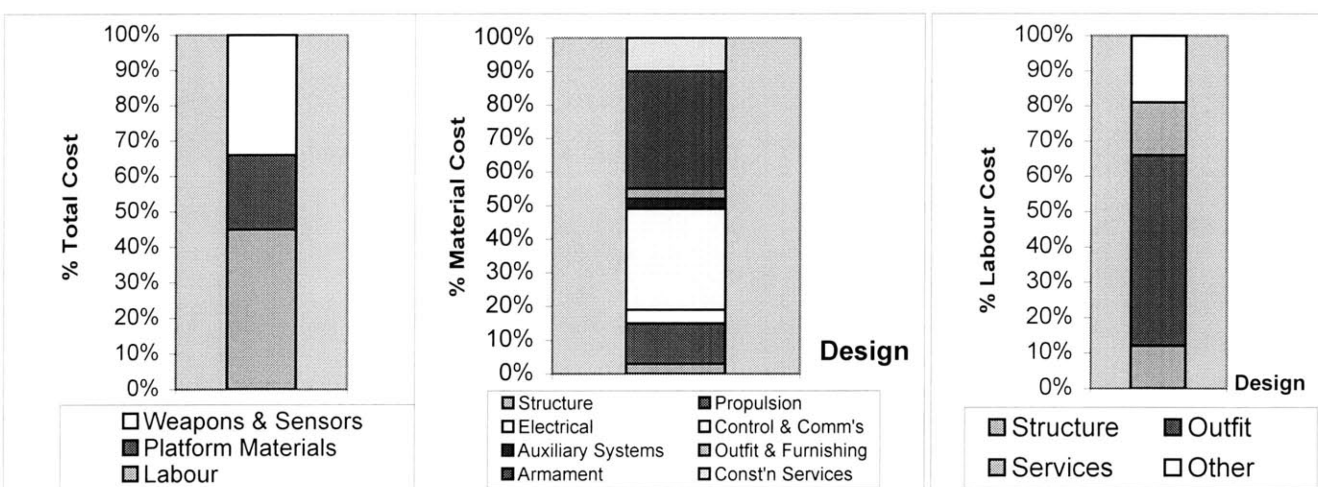


Figure 49. Cost Breakdown for a typical corvette design. [Ref 47]

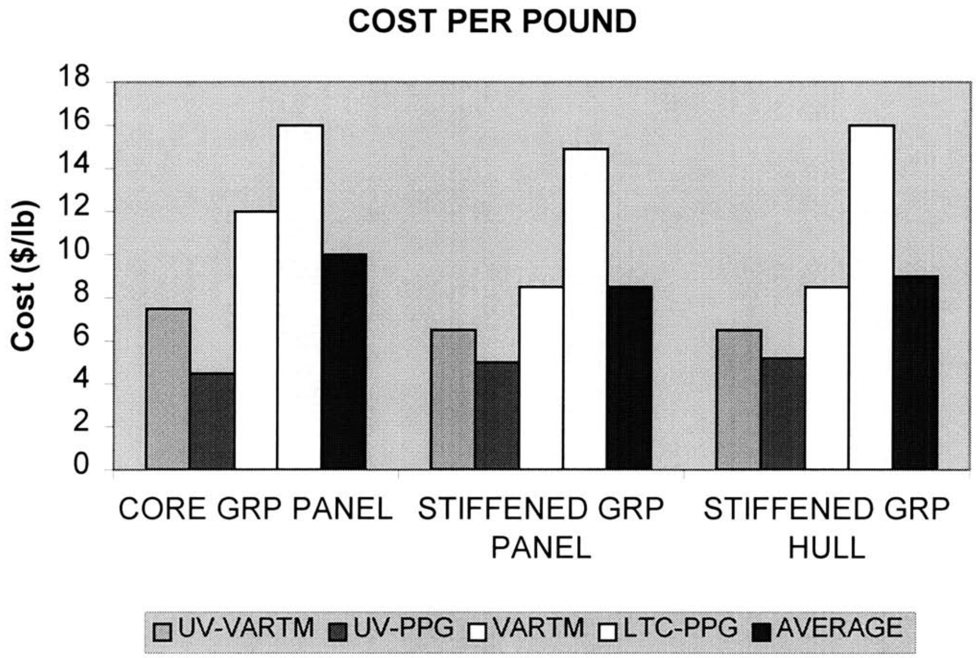


Figure 50. Production Cost per pound for different types of FRP Ship Structures. [Ref 47]

Current, most structural components of U.S. Navy/Department of Defense aircraft are made of fabricated aluminum. Although this approach is technically effective, its manufacturing and inventory costs can be enormous and the lead-time for critical parts can be long. Casting technology, on the other hand, offers substantially lower costs, because, castings can produce unitized components. Provided that the castings meet technical application requirements, larger-scale implementation could provide substantial cost savings to the marine community. To qualify, however, the mechanical properties of castings must meet application requirements the first time and every time.

For example, implementations of structural aluminum castings in aircraft applications are forecasted to reduce current manufacturing costs by more than 50 percent. Considering that manufacturing costs of current components are significantly high (in the $10,000-$100,000 range per complex part), total savings will amount to millions of dollars per component/per aircraft system basis.[13]

5.6.1 The Composite Structures Concept

Composite structures started with the objective of filling the niche between the aerospace composite and the tub & shower fiberglass manufacturers. This niche largely comprises the commercial and industrial sectors, which have been using traditional materials such as aluminum, steel, or wood as structural or architectural building materials of choice. [Ref 7]

However, as consumers demand better performance in the areas of weight, corrosion resistance or esthetics without sacrificing strength and durability, more and more companies in the commercial and industrial sector are turning to composite materials. Composite structures provide the capability for many companies to move to composites. Making the choice to move to composites is more difficult than it appears at first glance. Many companies have tried and failed to make the switch to composites by shear virtue of the complexity of composites. Unlike traditional materials, composites tend to be non-linear materials. In layman's terms that means that there are no easy formulas, code books, or design manuals with which engineers can use to design or even predict the performance of composite materials. Using design principles learned from years of designing in steel or aluminum will usually yield a very expensive product that ultimately fails the test of endurance. Composite structures have one of the most comprehensive design, development, and manufacturing teams available anywhere. [Ref 10]

5.6.2 Strategic Planning

The goal of strategic planning is to define the criteria upon which the final product is based, define the procedure for obtaining any unknown criteria, baseline the schedule

---

[13] METALWORKING TECHNOLOGY UPDATE, Fall-1999, Concurrent Technologies Corporation.

development, and establish the basis for a working relationship and lines of communication. The specific objectives include the following:

-Provide overview of production and design of fiberglass composites.

-Identify properties of materials used.

-Define design parameters of client's product.

-Outline aesthetic objectives, including examples if feasible

-Identify project schedule and areas of responsibility.

Construction costs for both the steel ship and the composite ship can be developed by standard shipyard cost-estimating procedures. This, however, is costly and time-consuming. A simpler method is needed, particularly when the study involves more than one new ship.

5.7 Use of Composites in the Shipbuilding Industry

A review of the costs associated with the current philosophy for the manufacturing phase of a composite product produces the breakdown in the following figure:

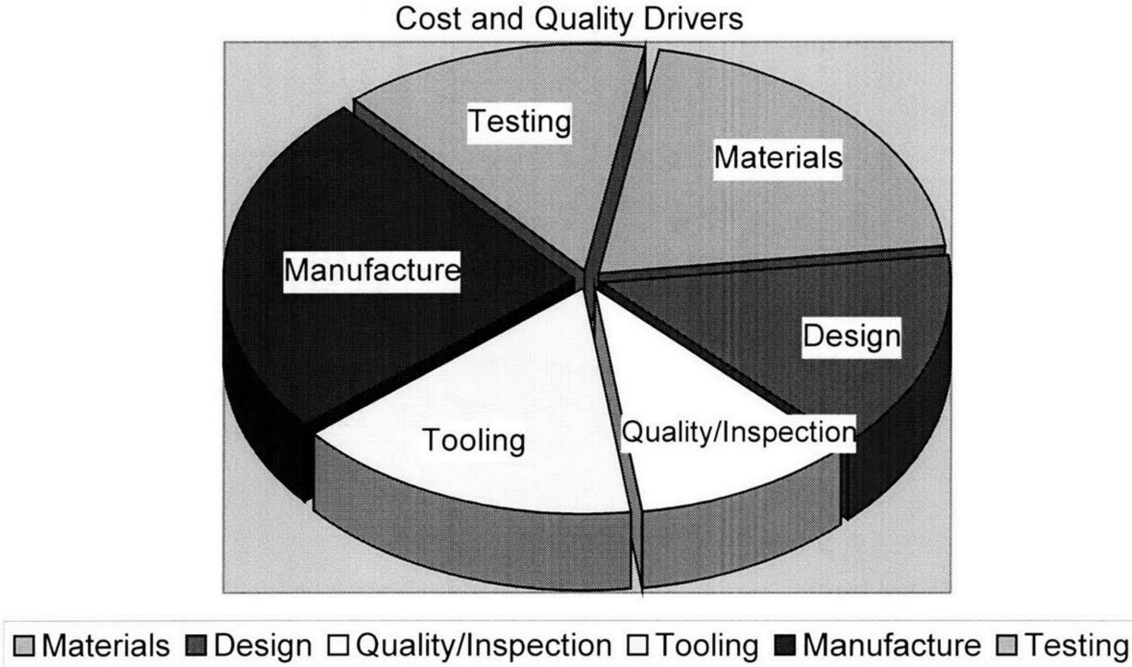


Figure 51: Cost and Quality Drivers for Composite Structures. [Ref 99]

The labor constituent represents approximately twice the direct costs of tooling and materials. Further, the direct manufacturing cost for operators and production engineers is half of the total labor cost, because there are number of activities which are performed off-line during the various stages of manufacture. These include: (1) testing of representative test-pieces during element manufacture (for example panel lay-up), (2) testing of representative details (for example bonded joints), (3) validation of operations to confirm that they have been performed (involving inspection and subsequent validation of these activities) and (4) confirmation of the subsystem performance (including environmental testing). These activities therefore introduce costs associated with test-piece manufacture, testing, and interpolation by design and product inspection. While the cost distribution associated with composite manufacture can be accommodated for current manufacturing rates, it would make it difficult to achieve the desired cost and production rate targets. It is therefore necessary to reduce the requirements for verification of part performance, through the development and adoption of robust manufacturing processes, where critical control parameters can be monitored to verify that the process and therefore part performance is acceptable.

The shipbuilding industry is a turbulent business that experiences continuous long term changes. However, during the current decade, fundamental structural changes are taking place as the industry rationalizes, globalizes and, at the same time, re-organizes what is considered to be core business. These changes are taking place in order to reduce complexity, improve functionality and quality, and to increase the range of products at affordable prices.

The major challenges affecting ship design for shipbuilding companies are quality, cost, functionality and meeting increasing legislation requirements such as safety, emissions and recycling. These challenges are a reflection of a combination of environmental needs, customer wants, resource sustainability and the quality of community life. The ship remains central to the global economy. A very high percentage of the cost of the car is consumed in materials and processing. Efficient component design and manufacture is a critical element to ensure cost effective materials engineering. Cost and weight reduction are major industry wants together with effective recycling and tooling investment reduction. The breakdown and trends of the top 12 polymers are shown in the following table:

Table 24: Top 12 Plastics Usage by North American OEM's (ranked by 1990 use) (Source: Market Search, Inc, Toledo for the SMC Alliance)

Plastic Type	**1985**	**1990**	**1995**	**2000**
Urethane	233	203	220	232
Polypropylene	172	195	233	258
ABS	145	125	129	129
PVC	137	118	129	137
Nylon	89	93	110	136
Polyethylene	79	85	111	150
Polyester SMC (thermoset)	73	77	117	150
Polypropylene (EPDM modified)	18	45	66	84
Polyester (thermoplastic)	34	42	46	49
Polycarbonate	25	40	46	51
Alloy PPO Styrene	29	26	30	32
Acrylic	28	23	26	28
Total (thousands of tones)	**1062**	**1194**	**1263**	**1436**

The use of fiber reinforced composites is growing. In 1996, America absorbed about 42% of the world composite sales with transportation taking the 25% of the global composites market. The threat of reduction in the use of steel and the increase in plastics, aluminum, composites and magnesium has led to the formation of the global ULSAB consortium of 32 steel companies to optimize steel automotive body design. The ULSAB consortium has set goals of reducing steel automotive average body weight by 25-35% by the use of high strength steels. The composites industry has made a start with a similar strategy. Thirty composite suppliers in the SMC Alliance are pooling resources to be more coordinated and competitive.

The use of composites materials is slowly growing as issues of cost, cycle time, impact modeling, quality, fit and finish, painting, waste and recycling are gradually being overcome.

However, if the shipbuilding industry is to make the breakthrough into the next generation of ships and advanced polymer composites are to play a greater role, then suppliers must start to form further alliances and work in greater co-operation, sharing technology to solve these real manufacturing open issues, and exploit the potential of composite materials.

5.8 Producibility Issues

The intention in this thesis is to highlight, from a shipbuilder's perspective, the main producibility issues to be addressed by marine researchers, designers and fabricators for the application of composites to larger marine vessels, where, due mainly to cost considerations, steel has traditionally been the preferred material. [Ref 72]

FRP was originally selected for reasons of low magnetic signature and good shock resistance, but many secondary benefits have also emerged and FRP composites now have a proven track record as a practical shipbuilding material.

For many years in the marine sector an unsophisticated approach to design and manufacture of composite structures has prevailed, compared with the advances made in the aerospace industry. This perhaps is not surprising considering that relatively low levels of funding available for ship research and the fact that for many years steel and aluminum have been considered quite satisfactory in service. Conversely for the aerospace sector advances in composites technology have been driven by a need to save weight at relatively high levels of acceptable cost.

This contrast between the two industry sectors is compounded by the market difference in size, weight and numbers of moldings required. Due to the relatively large size and low volume of production, marine composites have traditionally been characterized by low fiber volume fraction, variable quality, high void content materials, normally comprising E-glass fiber fabrics and polyester resin, produced by the manual open mould wet lay-up (hand lay-up) process. Specialist warships such as mine countermeasures vessels, where 30 years ago FRP began to replace wood as the main construction material, have resulted in the hand lay-up process approaching its limits in terms of laminate quality and performance, as a result of high levels of quality control.

However, with the recent advent of resin infusion processes available to large marine structures, a means of producing consistently high quality materials and structures now exists, which is not only cost effective, but also meets anticipated limits on emissions of volatile organic compounds (VOC) into the environment. This coupled with a deeper understanding of their behavior in a marine environment is prompting a re-assessment and expansion of the application of FRP composites on large military and commercial vessels for both primary and secondary structures.

5.9 Weight and Cost Considerations

Cost analyses carried out in the early stages of designing a composite structure can be problematic. For example, fabrication and assembly differ widely and the cost implications of specifying composite materials may extend far beyond the structure. This problem has led to the commissioning of large-scale technology demonstrators as a risk reduction measure and to aid the identification of cost drivers for composite structures for composite structures with a significant novel element.

There is a constituent material cost ratio of at least 3:1 by weight compared with steel for a basic E-glass and polyester combination. When core materials and EM screening are included this can increase to 5:1. However, a minimum cost structure does not equate a minimum cost ship. Cost savings are quite possible for structures of complex shape, or when a single composite part can replace an assembly comprising a large number of steel components, when fabrication man-hours can be greatly reduced. In the case of ship superstructures, the need to minimize weight leads in steel structures to very thin plating and subsequently weld distortion problems requiring laborious flame-straightening to achieve an acceptable degree of fairness. Extensive re-work of this nature can be extremely disruptive to a steel ship's build program.

A significant weight reduction of a vessel can have a knock-on effect on other aspects.

For example smaller engines, reduced engine support structure and fuel requirements may be possible. Lower displacement in a small high performance vessel like a patrol boat results in lower slamming pressures.

Composites do not require painting for protection against the marine environment, only for anti-fouling, non-skid on decks and aesthetics. Furthermore, with the use of pigmented resin and taking into account the insulating properties of the material, assembly, outfitting and finishing time may all be considerably less. Another benefit for warships is the ability to incorporate stealth materials for reduced radar, acoustic and infrared signature within the structure rather than as items added separately.

In a ship of traditional steel construction the structure typically accounts for 50% of lighting weight, whereas its cost is typically only 5-10% of the procurement cost of the vessel, depending on the weapons fit. Structure is thus the lowest cost and highest weight component. The steel weight of ships for a given role is gradually rising as warship builders are under increasing pressure to design to commercial standards, reduce production man-hours by making structures simpler, whilst still of course meeting classification society rule requirements. This facilitates technology transfer to overseas yards. However, from the foregoing it can be seen that by using composites, there is actually considerable scope to permit an increase in the cost of structure in order to achieve a cost saving overall:

1. Lower cost outfitting (increased internal volume, reduced painting, insulation and first fittings)

2. Reduced weight (increased stability, payload, speed or range, or reduced powering)

3. Reduced through-life cost (corrosion and fatigue related problems virtually eliminated)

4. Integrated technologies (incorporation of stealth materials, smart materials).

5.10 Evaluation of Non-Economic Factors

Non-economic considerations are always less important than economic considerations in evaluating the worth of a merchant ship. Non-economic factors must, however, be considered in any complete evaluation. Many such factors have an effect on the owner's expectation of profit, even though that effect cannot be expressed in dollars. For example, the appearance of the ship may improve or degrade the reputation of the company in the eyes of the public and the financial institutions, and thus affect the availability of funds; or the risks associated with a particular material may increase or decrease the likelihood of unpredictable costs during the life of the ship. We can define five typical types of non-economic factors:

I. Suitability for Intended Use

II. Environmental Impact

III. Use of National Resources

IV. Government Involvement, and

V. Risk

The effects of these non-economic factors are usually significant only when the difference in RFR is small, but in some cases they may change the result from 'favorable' to 'unfavorable' or vice versa. A method for measuring these effects systematically has to be developed in order to combine them with the results of the economic analysis to obtain a single numerical measure of worth.

6 An example

6.1 Ship Model

In order to validate the results of this study, an application to a complete model was performed. The selection is a trimaran vessel designed at the Department of Ocean Engineering of Massachusetts Institute of Technology for the U. S. Navy. The following standards were used for this design:

- Structural strength: DDS 100-1, 2, 4, 5, 6, 7
- Shock: DDS 072-1, 150-1
- Nuclear Blast: DDS 072-2

The standards listed above represent accepted and proven criteria that must be met by the designer of the vessel. In order to deviate from these design standards, significant improvement of the mission performance has to be demonstrated and approved. The main characteristics of this vessel are presented at the following table:

Table 25. Main characteristics of the LHA(R) Trimaran.

Length (ft)	550
Beam (ft)	160
Lightship Displacement (Ltons)	3525
Draft (ft)	40
KG (ft)	29.08

6.2 Steel vs. Composites

The vessel was initially designed out of steel and then was designed with carbon fiber and vinyl ester matrix. A preliminary phase structural analysis, using typical U.S. Navy structural design practices, was performed to determine if the LHA(R) Trimaran ship concept was structurally feasible and to aid in the development of the final, preliminary three-digit weight estimate.

In order to evaluate the structural performance of the trimaran the finite element analysis tool MAESTRO was used. MAESTRO offers the designer the capability of optimizing the scantlings of the ship for given loading conditions. The structural design of the conceptual hull geometry was initiated by designing a midship section of the trimaran vessel, using the dimension of the scantlings similar to the ones from the DDG51. Figure 52 presents the initial model.

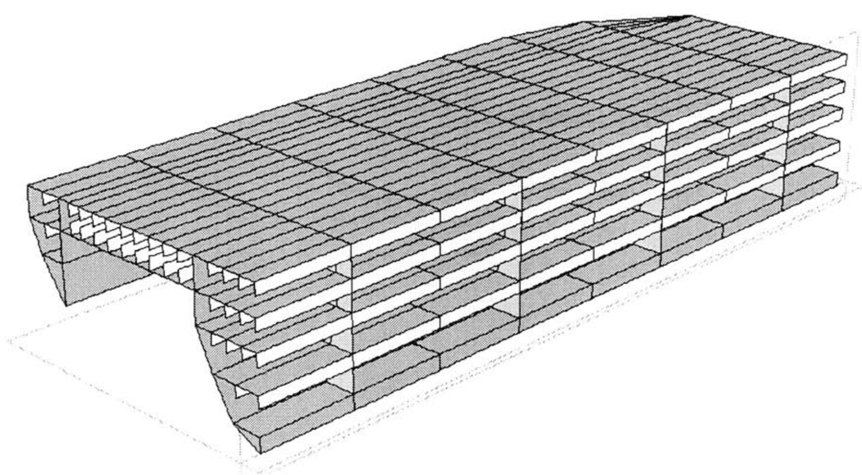


Figure 52. Midship section of the LHA(R) Trimaran.

Furthermore, and due to the nature of the trimaran structural configuration, the whole vessel was modeled and evaluated. For the structural analysis of this design to major loading cases were evaluated:

- Hogging bending moment combined with hogging wave

- Sagging bending moment combined with sagging wave

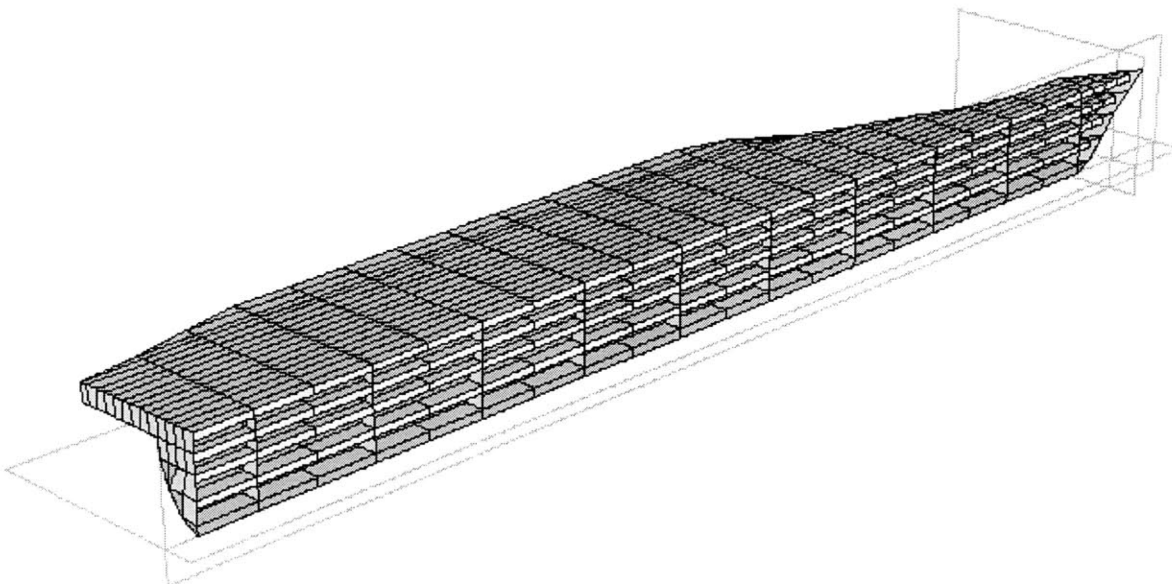


Figure 53. Whole finite element model of the LHA(R) Trimaran build at MAESTRO.

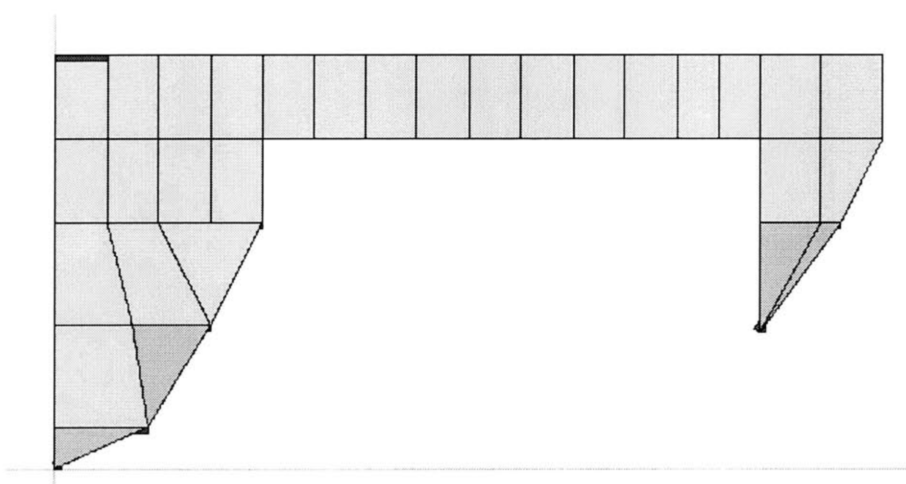


Figure 54. Cross deck body plan of the trimaran vessel.

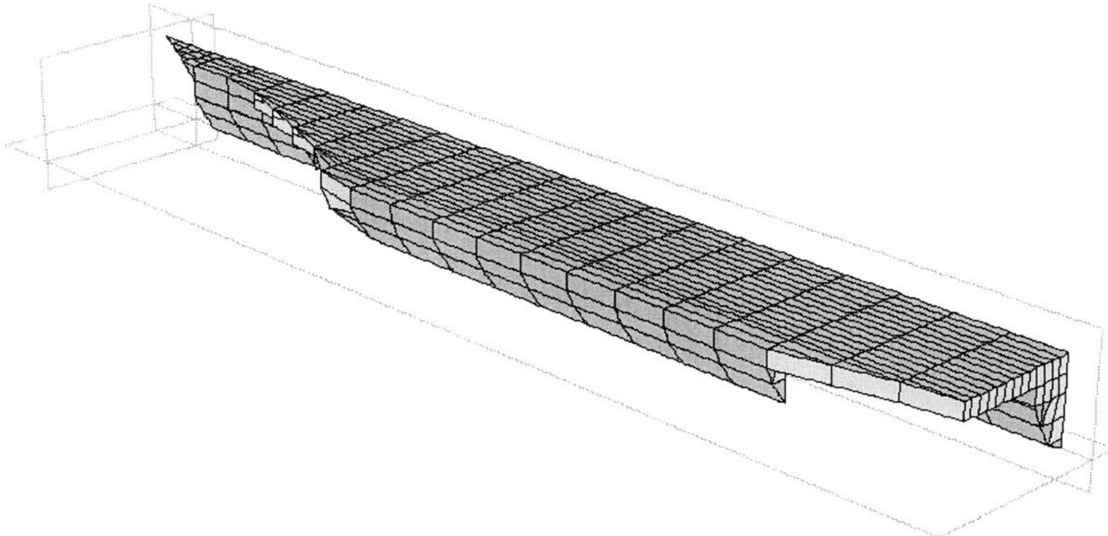


Figure 55. Starboard quarter bow view of the LHA(R) Trimaran.

6.3 Cost comparison

For this evaluation the following assumptions were made:

- Number of Ships: 6
- Ship Service Life: 35 years
- Production Rate: 1 ship annually
- Initial Operational capability: 2015
- Average Inflation Rate: 3%
- Discount rate: 10%

Detailed analysis of the cost model and calculations are presented in Appendix 1. The final results are presented in Table 26.

Table 26. Comparison between the steel and the composite designs.

	Steel Trimaran	**Composite Trimaran**	**Difference (%)**
Weight (Ltons)	3525	1938	45
Total Lead Ship Acquisition Cost ($M)	40.21	25.23	37
Total Discounted Life Cycle Cost ($M)	116.58	91.7	21
Average Ship Acquisition Cost ($M)	30.78	19.44	37

7 Conclusions and Recommendations

This study investigated the application of marine composites to the design and construction of surface vessels which overall length exceeds 100 m. It is typical that for the same longitudinal strength, composites result in larger hull flexibility than more conventional shipbuilding materials. Therefore the dynamic behavior in the form of hull girder deflection caused by continuous wave action and wave slamming impact must be expected to depend on the selected construction material. In order to take advantage of increased strength to weight ratios that composites present the designer should not in any case sacrifice the adequate stiffness of the structure.

The methodology that was incorporated for this study in order to approach the wide variety of solutions to this problem is described at the following steps:

1. Four different design concepts were explored by using elimination of structural components, such as frames and girders, in order to define their contribution to the structural performance of the composite structure.

2. For all the design concepts, a set of loading conditions was imposed, which included combination of bending moments and waves, slamming, green seas, live loads and hydrostatic pressure.

3. Based on three selected criteria, which include weight and cost reduction, maximum deflections and complexity of manufacturing, all four designs were analyzed, and the selected one was in-depth evaluated concerning weight, cost and structural performance.

The results of this study can be summarized as follows:

- existing composite materials have adequate strength for designing "large" ships

- life cycle cost of a composite hull structure can be less than the steel one due to significant weight and maintenance reductions

- a design stiffened longitudinally and transversely (with stiffeners and girders), constructed from carbon (or combined with glass) based composites is a feasible and affordable solution for "large" ship constructions

- a number of major technical and economic aspects are still questionable

In order to optimize the design of composite structures, it is essential to have confidence in the mechanical property data, which is employed. This is true for all applications and the aeronautical industry has spent much effort on the standardization of test methods and the establishment of confidence levels for design purposes. Although for certain critical applications the marine industry does use high performance materials, many of the composites used for marine applications are very different from their aerospace counterparts, both in terms of the constituents and the fabrication techniques. High-speed warships are weight-sensitive structures and high-strength steel or advanced composites are the preferred construction materials.

A weight saving of 50% compared to conventional steel design is realistic without increasing the total cost of the construction, in case the designer wants to consider higher safety factors compared to the ones used for steel constructions. The reduction in weight achieved by using advanced composites allows increased ship performance by extending the range and speed of the ship for either constant propulsive power or increased payload.

Composites are more amenable than steel for block construction and pre-outfitting. The working environment is cleaner and quieter, there is no hot work, and there is a reduced requirement for application of materials potentially harmful to health such as paint and insulation. It is easier to make blocks of structure stable and self-supporting without the need for temporary stiffening because all minor partitions can be fully integrated and made structural.

7.1 Recommendations for future work

The designs examined in this study are not the unique solutions for the application of composite materials in the shipbuilding industry. Several alternatives have to be evaluated prior to the selection of the appropriate design. Figure 56 presents another alternative to the application of composite materials.

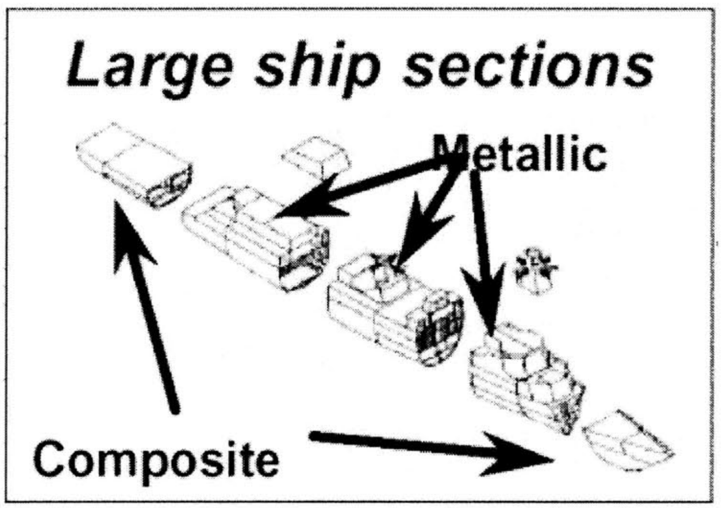


Figure 56. Alternative design for further examination.

Further investigation is required in the following areas:

- A careful analysis of the interlaminar stresses, especially for special loading conditions, such as collision, grounding and blast loading
- Examination of fatigue and fracture phenomena of marine composites has to be performed prior to a wide application in large structures
- Selection of safety factors has to be relied on the gaining experience of the designer and shipbuilder, in order to build a sound structure
- Bonding and joining techniques

- Fire performance of marine composites has to be in accepted levels, which are stated in the classification societies

It has often been stated that when replacing steel with composites, it is important not to merely make the composite component look like the metal one it replaces but to re-design the structure from first principles. This can be difficult for any new applications where steel has been established for many years because it is quite likely that the mechanical, electrical, thermal, chemical and fire properties of steel have by this time been accepted without question. The first stage in such cases must be to ask –'what must the part do?' and create from scratch a detailed performance specification for the material/structure, then adopt a topology which acknowledges the anisotropic nature of laminated materials, considers how the structure would be fabricated and optimizes the mechanical properties of the laminate and physical characteristics of the constituent fabrics and resins. The end result could look radically different from its steel counterpart and one should not underestimate the problem of overcoming resistance and prejudice which are bound to exist before the composite concept gains acceptance.

List of References

Ref 1: Valery V. Vasiliev and Zafer Gurda, "Optimal Design", Theory and Applications to Materials and Structures, Technomic Publishing Co, Inc, Lancaster, Basel, 1999.

Ref 2: Autar K. Kaw, Mechanics of Composite Materials, CRC Press, Boca Raton N.Y., 1997.

Ref 3: Robert J. Scott, Fiberglass Boat Design and Construction, John de Graff Inc., Tuckahoe N.Y., 1973.

Ref 4: Greene Eric, Use of Fiber Reinforced Plastics in the Marine Industry, Ship Structure Committee, SSC-360, 1990, Springfield, VA: National Technical information Service.

Ref 5: Raymer J. F., "Large-Scale Processing Machinery for fabrication of Composite Hulls and Superstructure", Journal of Ship Production, Volume 7, No. 4, November 1991, pp. 220-226.

Ref 6: Dow R. S. and Bird J., "The Use of Composites in Marine Environments", Structural Materials in Marine Environments, Proceedings, 11-12 May, The Royal Society, London, UK, 1994.

Ref 7: C.S. Smith, Design of Marine Structures in Composite Materials, Elsevier Science Publishing Co. Inc., New York N.Y., 1990.

Ref 8: Robert J. Scott, John H. Sommella, Feasibility Study of Glass Reinforced Plastic Cargo Ship, Ship Structure Committee, SSC-224, 1971.

Ref 9: A.W. Horsmon, "Composites for Large Ships", Journal of Ship Production, Volume 10, Number 4, pg 274-280, 1994.

Ref 10: NAVY 2000, Symposium Proceedings, 7-8th June 2000, Karlskrona, Sweden.

Ref 11: P. Cahill, "Composite Materials and Naval Surface Combatants: The Integrated

Technology Deckhouse Project", Journal of Ship Production, Volume 8, Number 1, pg 1-7, 1992.

Ref 12: http://www.naval-technology.com/projects/visby/index.html

Ref 13: http://www.canit.se/%7Egriffon/diverse/miltech/stealthships.html

Ref 14: Greene Eric, Design Guide for Marine Application of Composites, Ship Structure Committee, SSC-403, 1997.

Ref 15: http://www.kockums.se/SurfaceVessels/visby.html

Ref 16: http://www.instmat.co.uk/iom/organisations/escm/ship.pdf

Ref 17: http://www.janes.com/defence/naval_forces/news/jni/jni000622_2_n.shtml

Ref 18: D.H. Middleton, Composite Materials in Aircraft Structures, Longman Group, U.K., 1990.

Ref 19: G.H. Staab, Laminar Composites, Butterworth – Heinemann, Woburn, MA, 1999.

Ref 20: P. Goubalt, S. Mayes, "Comparative Analysis of Metal and Composite Materials for the Primary Structures of a Patrol Craft", Naval Engineers Journal, Volume 108, Number 3, pg 387-397, 1996.

Ref 21: Cindy Foreman, Advanced Composites, IAP Inc., Casper, WY, 1990.

Ref 22: International Systems LLC, Littoral Support Craft Final Report, August 1999.

Ref 23: Robert M. Jones, Mechanics of Composite Materials, Taylor & Francis Inc., Philadelphia, PA, 1999.

Ref 24: Stephen W. Tsai, Theory of Composites Design, Think Composites, Dayton, OH, 1992.

Ref 25: Mahmood H. Datoo, Mechanics of Fibrous Composites, Elsevier Applied Science, London, U.K., 1991.

Ref 26: Ranjit Roy, A Primer on the Taguchi Method, Van Nostrand Reinhold, New York, NY, 1990.

Ref 27: Sung H. Park, Robust Design and Analysis for Quality Engineering, Chapman & Hall, St Ednundsbury Press Ltd, Bury St Edmunds, Suffolk, 1996.

Ref 28: Yoshiko Yokoyama, Taguchi Methods – Design of Experiments, American Supplier Institute Inc., Dearborn, MI, 1993.

Ref 29: Genichi Taguchi, Introduction to Quality Engineering, Asian Productivity Organization, Hong Kong, 1992.

Ref 30: Owen F. Hughes, Ship Structural Design – A Rationally Based, Computer Aided Optimization Approach, Society of Naval Architects and Marine Engineers, 1998.

Ref 31: MAESTRO© Manual – Ver. 8.0, Proteus Engineering, 1999.

Ref 32: Department of Defense, Interactive Composites Handbook MIL-HDBK-17-2D, 1997.

Ref 33: S.T. Peters, Handbook of Composites 2nd Edition, Chapman & Hall, 1998.

Ref 34: D.F. Hasson and C.R. Crowe, Materials for Marine Systems and Structures, Academic Press, Inc., 1988.

Ref 35: Judith Ray Hazen, "High-Performance Composites: An Overview", Journal of High-Performance Composites, Vol. 8, No. 6, International Edition, November 2000.

Ref 36: Third International Conference on Marine Applications of Composite Materials, March 19-21, 1990, Florida Institute of Technology, Melbourne, FL USA.

Ref 37: Application of composites in a marine environment: status and problems, Peter Davies, pp. 33.

Ref 38: Lowell E. Smith, et. al., Shipbuilding and Ship Design perspectives on applications of composite materials: capability drivers and technical issues, 37th International SAMPE

Symposium, pp. 63-77, March 9-12, 1992.

Ref 39: J. E. Slater and R. Houlston, Selection of GRP composites for naval ship structures. In Sih GC, Pindera JT, editors, Development and design with advanced materials. Amsterdam: Elsevier; 1980. p. 289-300.

Ref 40: O. Gullberg and K. –A. Olsson, Design and Construction of GRP Sandwich Ship Hulls, Marine Structures 3 (1990) pp. 93-109.

Ref 41: A. R. Dodkins & T. J. Williams, Sandwich structures for naval vessels. In: Proceedings of the International Conference on Offshore and Marine Composites, Newcastle UK, 2000 April 5-6.

Ref 42: S. –E. Hellbratt and O. Gullberg, The development of the GRP-sandwich technique for large marine structures, Sandwich Constructions.

Ref 43: R. F. Beale, Selection of Glass-Reinforced Plastics Materials for Large Marine Structures, British Polymers Journal, 1971, Vol. 3, January.

Ref 44: Sea Duty for Composites?, Advanced Materials & Processes, 1992; 142(2):16-20.

Ref 45: Carbon fibre composite for Sweden's next generation corvette, Maritime Defense, 1996;21:111-4.

Ref 46: Milton O. Critchfield and Thomas D. Judy, Low-cost Design and Fabrication of Composite Ship Structures, Marine Structures 7 (1994) pp. 475-494.

Ref 47: R. D. Mulligan, Courts M. D., Corvette Design Considerations. In: Proceedings of Warship '98: International Symposium on Surface warships: The Next generation, London, 1998 June 11-12. Paper No. 6.

Ref 48: K. B. Spaulding, Jr, A history of the construction of fiberglass boats for the Navy, Bureau Ships Journal 1996; 15:2-11.

Ref 49: Karen J. Fisher, Is fire a barrier to shipboard composites?, Advanced Composites, May/June 1993, pp. 20-26.

Ref 50: M. O Critchfield, Morgan, S. L. and Potter, P. C., "GRP Deckhouse Development for Naval Ships," presented at the International Conference on Advances in Marine Structures, 21-24 may 1991, Admiralty Research Establishment, Dunfermline, Scotland.

Ref 51: C. S. Smith and P. Murphy, Response of hybrid GRP/Steel superstructures to blast loading –Theory and Experiment. Advances in marine structures – 2. London: Elsevier; 1991. p. 392-415.

Ref 52: ASSET Manual concerning Structural Design Loads.

Ref 53: Norway's New FRB starts trials, Warship Technology, August 1999.

Ref 54: David Lyons, The use of high Ductility Core material in the sandwich structure of the YS2000 *Visby* class corvette. In: Proceedings of ACUN-2, Syndey, 2000 February 14-18. p. 710-13.

Ref 55: Anders Lönnö, The Visby class corvette: the worlds biggest CFRP-Sandwich ship. In: Proceedings of the Conference on Offshore and Marine Composites, Newcastle, UK, 2000 April 5-6.

Ref 56: Robin Burnett, Minehunters and minesweepers on stream for the next century. Naval Architecture 1996:66-70.

Ref 57: Reid Phelan, Design, Analysis, fabrication and testing of a composite control surface, Naval Engineers Journal, March 1995, Vol. 107.

Ref 58: D. K. Brown, Design considerations for MCMV. Naval Forces 1990;11(1):31-8.

Ref 59: Anders Lönnö, Experiences from using carbon fiber composites/sandwich construction in the Swedish Navy. In: Proceedings of the Fourth international Conference on Sandwich Construction, Stockholm, 1998 June 9-11. p. 31-43.

Ref 60: The Skjold class fast patrol boat. Naval Forces 5 (1999), pp. 38-43.

Ref 61: J. Sjörgen et. al., Swedish development of MCMV-Hull design and production. In: Proceedings of the International Symposium on Mine Warfare Vessels and Systems, London, 1984.

Ref 62: D. J. Hall and B. L. Robson, A review of the design and materials evaluation programme for the GRP/foam sandwich composite hull of the RAN minehunter, Composites, Volume 15, No. 4, October 1984, pp. 266-76.

Ref 63: Richard D. Hepburn et. al., The U.S. navy's new coastal minehunter (MHC): Design, Material, and Construction Facilities, Naval Engineers Journal, May 1991, 103(3):60-73.

Ref 64: The Eridan class: France's Tripartite minehunters. Naval Forces 1991;12(5)66-7.

Ref 65: J. Steven Mayes and Robert J. Scott, Advanced all-composite surface combatant. In: Proceedings of the American Society of Naval Engineers (ASNE) Symposium, Vol. 1, Biloxi, Mississippi, 1995. p. 16-17.

Ref 66: W. Remen, The use of FRP sandwich. In: Proceedings of the International Conference on Nautical Construction with Composite Materials, Paris, 1992 December 7-9. Paper 42.

Ref 67: D. J. Creswell et. al., Composite rudder steers into the future. In: Proceedings of the International Conference on Advances in Marine Structures III, Dunfermline, 1997 May 20-23.

Ref 68: W. Gass et. al., Fabrication and Testing of a prototype corrugated GRP hull, Journal of Naval Science, 1987, Vol. 13, No. 3, pp. 187-97.

Ref 69: Jeremy R. Smith et. al., A foam sandwich submarine hull DERA "Novel Hull Model No 1", Warship 1999.

Ref 70: Loc B. Nguyen and Milton O. Critchfiled, Feasibility study and fabrication demonstration of FRP hull structures for naval surface combatants.

Ref 71: J. E. Slater, Selection of a Blast-Resistant GRP composite panel design for naval ship structures, Marine Structures 7 (1994) 417-440.

Ref 72: Loc B. Nguyen, et. al., "Design and Fabrication of Large composite primary ship hull structures".

Ref 73: D. J. Eyres, Stresses to which a ship is subject, Ship Construction, 3rd ed., Heinemann professional publication, London, 1972.

Ref 74: N. Bekiaris, Selection of Composite Materials for the Construction of Large Ships, May 2000, Master Thesis at Massachusetts Institute of Technology.

Ref 75: Hakan Enlund, Development of Large Composite applications in ship building, Composites and Sandwich Structures.

Ref 76: A. P. Mouritz et. al., "Review of advanced composite structures for naval ships and submarines," Composite Structures 53 (2001) pp. 21-41.

Ref 77: Anthony Kelly and Carl Zweben, Comprehensive Composite Materials, Volume 6, Design and Applications.

Ref 78: Sarah E. Mouring, Composites for Naval Surface Ships, Marine Technology Society Journal, 32 (2): 41-46, Summer 1998.

Ref 79: M. F. Ashby, Materials Selection in Mechanical Design, Materials and Process Selection Charts, Pergamon Press.

Ref 80: Kevin Potter, An introduction to composite products, Published by Chapman & Hall

Ref 81: Krishan K. Chawla, Composite Materials, 2nd Edition, 1998.

Ref 82: Ever J. Barbero, Introduction to Composite Materials Design, Published by Taylor & Francis, Inc., 1998.

Ref 83: P. Davies & P. Chauchot, Composites for Marine Applications, Part 2. Underwater Structures, Mechanics of Composite Materials and Structures, pp.249-260, 1999, Kluwer

Academic Publishers.

Ref 84: Jack R. Vinson, Sandwich structures: Origins, Advantages and uses, The behavior of Sandwich Structures of Isotropic and Composite Materials, 1999.

Ref 85: Stephen R. Swanson, Fibers, An Introduction to design and analysis with advanced composite materials, 1999.

Ref 86: Gunnar Holm, Sandwich in marine structures-Challenges and solutions for the structural designer, Sandwich Construction 4, Volume I, 1998.

Ref 87: Anders Lönnö, Experiences from using carbon fiber composites/ sandwich construction in the Swedish navy, Sandwich Construction 4, pp. 31-43, 1998.

Ref 88: S. D. Clark and R. A. Shenoi, Comparative study on the fatigue performance of sandwich structures, Sandwich Construction 4, pp. 45-53, 1998.

Ref 89: K.-E. Mäkinen, S.-E. Hellbratt and K.-A. Olsson, The development of sandwich structures for naval vessels during 25 years. In: Vautrin A, editor. Mechanics of Sandwich Structures, Proceedings of the EUROMECH 360 Colloquium , 13-15 May. Kluwer Academic Publishers: Netherlands; 1988. pp. 13-28.

Ref 90: Anders Lönnö and Sven-Erik Hellbratt, Use of Caron fibre in a 63m High-speed vessel, YS2000, for the Swedish navy. In: Proceedings of the Third International Conference on Sandwich Construction, Southampton, 1995 September 12-15, p. 3-13, Volume I.

Ref 91: T. Juska et. al., Mechanical Properties and impact resistance of fabric reinforced vinyl ester, MACM 1992 Conference Proceedings, March 1992.

Ref 92: Eric Greene, Fire performance of Composite materials for naval applications, MACM 1992 Conference Proceedings, March 1992.

Ref 93: Ronnal P. Reichard, "Materials Selection for Boats and Ships," Third International Conference on Marine Applications of Composite Materials, March 1988, Melbourne, FL.

Ref 94: Bryant Bernhard, The first of a class: production of large military FRP displacement hulls.

Ref 95: Peter Davies, Application of composites in a marine environment; status and problems.

Ref 96: Preben Terndrup Pedersen, Global Loads on FRP Ship Hulls, Composite and Sandwich Structures.

Ref 97: Michael Valenti, Stealth on the water, Mechanical Engineering, January 2001, pp. 561.

Ref 98: Sven-Erik Hellbratt and Sten Vallbo, Practical aspects on structural analysis of a weight optimized FRP-sandwich stealth corvette, Sandwich Construction 4.

Ref 99: F. N. Scott, "Quality challenges for the space industry to achieve cost and cycle-time reductions," ImechE conference Transactions, 15-16 September 1998, London, UK.

Ref 100: J. E. Gagorik et. al., "An overview of composite developments for naval surface combatants," 36th International SAMPE Symposium, April 15-18, 1991.

Ref 101: C. S. Smith et. al., "Design of Ship Superstructures in Fibre-Reinforced plastic," The Royal Institution of Naval Architects (RINA), Admiralty Research Establishment, Dunfermline, April 1986. Paper No. 3.

Ref 102: Albert W. Horsmon, "Lightweight Composites for Heavy-Duty Solutions," Marine technology, Vol. 38, No. 2, April 2001, pp. 112-115.

Ref 103: Personal communication with Sven-Erik Hellbratt.

Ref 104: Personal communication with Loc B. Nguyen.

List of Appendices

Appendix 1

COST MODEL

MIT 13A

Definitions (units): $Mdol := coul$ $Bdol := 1000 \cdot Mdol$ $Kdol := \frac{Mdol}{1000}$ $dol := \frac{Kdol}{1000}$

$lton := 2240 \cdot lb$

1. Single Digit Weight Summary:

$i1 := 100, 200 .. 700$

$W_{500} := 0 \cdot lton$ $W_{200} := 0 \cdot lton$ $W_{600} := 0 \cdot lton$ $W_{F_{20}} := 0 \cdot lton$ $W_{400} := 0 \cdot lton$ $W_{F_{23}} := 0 \cdot lton$

$W_{100} := 1938 \cdot lton$ $W_{IC} := 0 \cdot lton$ $W_{300} := 0 \cdot lton$ $W_{700} := 0 \cdot lton$ #

#

#

Weight margin: $W_M := 0 \cdot lton$ #

2. Additional Characteristics:

Lightship:

$$W_{LS} := \sum_{i1} W_{i1} + W_M \qquad W_{LS} = 1938 \text{ lton}$$

Costed Military Payload: (helo and helo fuel weight not included)

$$W_{MP} := \left[\left(W_{400} + W_{700} \right) - W_{IC} \right] + W_{F_{20}} - W_{F_{23}} \qquad W_{MP} = 0 \text{ lton}$$

$W_{MP} := 0 \cdot lton$

Installed Propulsion Power: $P_{SUM} := 0 \cdot hp$ #

$P_I := 0 \cdot hp$

Manning: (crew + air detachment + staff) **Officers:** $N_O = 0$ **Enlisted:** $N_E = 0$ #

Officers: $N_{C_1} := N_O$ **CPO's:** $N_{C_2} := 0$ **Enlisted:** $N_{C_3} := N_E - N_{C_2}$ #

Ship Service Life: $L_S := 35$ **Initial Operational Capability:** $Y_{IOC} := 2015$ #

Total Ship Acquisition: $N_S := 6$ **Production Rate (per year):** $R_P := 1$

3. Inflation:

Base Year: $Y_B := 1999$ $iy := 1 .. Y_B - 1981$ #

Average Inflation Rate (%): (from 1981) $R_I := 3.$ #

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 1.7$$

4. Lead Ship Cost:

a. Lead Ship Cost - Shipbuilder Portion:

SWBS costs: (See Enclosure 1 for K_N factors); includes escalation estimate

Structure

$$K_{N1} := \frac{.55 \cdot Mdol}{lton^{.772}} \qquad C_{L_{100}} := .03395 F_I \cdot K_{N1} \cdot (W_{100})^{.772} \qquad C_{L_{100}} = 10.97 Mdol$$

+ Integration/Engineering: (Lead ship includes detail design engineering + plans for class)

$$K_{N8} := \frac{10. \cdot Mdol}{Mdol^{1.099}} \qquad C_{L_{800}} := .034 K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{L_{800}} = 4.73 Mdol$$

+ Ship Assembly + Support: (Lead ship includes all tooling, jigs, special facilities for class)

$$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}} \qquad C_{L_{900}} := .135 K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839} \qquad C_{L_{900}} = 2.01 Mdol$$

a. Lead Ship Cost - Shipbuilder Portion (continued):

= **Total Lead Ship Construction Cost: (BCC)** :

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_{800}} + C_{L_{900}} + C_{LM} \qquad C_{LCC} = 17.71\,\text{Mdol}$$

+ Profit:

$$F_P := .10 \qquad C_{LP} := F_P \cdot C_{LCC} \qquad C_{LP} = 1.77\,\text{Mdol}$$

= **Lead Ship Price** :

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 19.48\,\text{Mdol}$$

+ Change Orders:

$$C_{LCORD} := .12 \cdot P_L \qquad C_{LCORD} = 2.34\,\text{Mdol}$$

= ***Total Shipbuilder Portion:***

$$C_{SB} := P_L + C_{LCORD} \qquad C_{SB} = 21.82\,\text{Mdol}$$

b. Lead Ship Cost - Government Portion

Other support: $C_{LOTH} := .025 \cdot P_L$ $\quad C_{LOTH} = 0.49\,\text{Mdol}$

+ Program Manager's Growth: $C_{LPMG} := .1 \cdot P_L$ $\quad C_{LPMG} = 1.95\,\text{Mdol}$

= ***Total Government Portion:***

$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT}$ $\qquad C_{LGOV} = 2.43\,Mdol$

c. Total Lead Ship End Cost: ***(Must always be less than appropriation)***

* ***Total End Cost:*** $\qquad C_{LEND} := C_{SB} + C_{LGOV}$ $\qquad C_{LEND} = 24.25\,Mdol$

d. Total Lead Ship Acquisition Cost:

+ Post-Delivery Cost (PSA): $\qquad C_{LPDEL} := .05 \cdot P_L$ $\qquad C_{LPDEL} = 0.97\,Mdol$

= Total Lead Ship Acquisition Cost:

$C_{LA} := C_{LEND} + C_{LPDEL}$ $\qquad C_{LA} = 25.23\,Mdol$

5. Follow-Ship Cost:

Learning Rate/Factor: $\qquad R_L := .97 \qquad F := 2 \cdot R_L - 1 \qquad F = 0.94$

a. Follow Ship Cost - Shipbuilder Portion

$$C_{F_{i1}} := F \cdot \frac{C_{L_{i1}}}{coul} \qquad C_{FM} := F \cdot C_{LM} \qquad C_{FM} = 0\,Mdol$$

$$C_{F_{800}} := \frac{.104}{Mdol^{1.099}} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \qquad C_{F_{800}} \cdot coul = 1.45\,Mdol$$

$$C_{F_{900}} := F \cdot \frac{C_{L_{900}}}{coul} \qquad C_{F_{900}} = 1.89$$

$$\frac{C_{F_{i1}} \cdot coul}{Mdol} =$$

10.31
0
0
0
0
0
0

Total Follow Ship Construction Cost: (BCC)

$$C_{FCC} := \sum_{i1} \frac{C_{F_{i1}} \cdot Mdol}{coul} + \frac{C_{F_{800}} \cdot coul}{Mdol} + C_{F_{900}} + \frac{C_{FM}}{Mdol} \qquad C_{FCC} \cdot coul = 13.65\,Mdol$$

+ Profit:

$F_P := .1 \qquad C_{FP} := F_P \cdot C_{FCC} \cdot coul \qquad C_{FP} = 1.36\,Mdol$

= FollowShip Price:

$P_F := C_{FCC} \cdot coul + C_{FP} \qquad P_F = 15.01\,Mdol$

F FCC FP F

+ **Change Orders:**

$$C_{FCORD} := .08 \cdot P_L \qquad C_{FCORD} = 1.56\,\text{Mdol}$$

= **Total Follow Ship Shipbuilder Portion:**

$$C_{FSB} := P_F + C_{FCORD} \qquad C_{FSB} = 16.57\,\text{Mdol}$$

b. Follow Ship Cost - Government Portion

Other support: $C_{FOTH} := .025 \cdot P_F \qquad C_{FOTH} = 0.38\,\text{Mdol}$

= ***Total Follow Ship Government Cost:***

$$C_{FGOV} := C_{FOTH} + C_{FPMG} + C_{FMPG} + C_{FHMEG} + C_{FOUT} \qquad C_{FGOV} = 1.13\,\text{Mdol}$$

c. Total Follow Ship End Cost:
(Must always be less than SCN appropriation)

* ***Total Follow Ship End Cost:***

$$C_{FEND} := C_{FSB} + C_{FGOV} \qquad C_{FEND} = 17.7\,\text{Mdol}$$

d. Total Follow Ship Acquisition Cost:

+ **Post-Delivery Cost (PSA):** $C_{FPDEL} := .05 \cdot P_F \qquad C_{FPDEL} = 0.75\,\text{Mdol}$

= ***Total Follow Ship Acquisition Cost:*** $C_{FA} := C_{FEND} + C_{FPDEL} \qquad C_{FA} = 18.45\,\text{Mdol}$

AVERAGE SHIP ACQUISITION COST:

$$C_{AV} := \frac{\dfrac{C_{FA} - C_{FMPG}}{F} \cdot (N_S - 1)^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} + (N_S - 1) \cdot C_{FMPG} + C_{LA}}{N_S} \qquad C_{AV} = 19.44\,\text{Mdol}$$

6. Life Cycle Cost:

a. Research and development

Ship design and development:

$$C_{SDD} := 1.2\cdot\left(.571\cdot\frac{C_{FSB}}{F} + .072\cdot C_{I.MPG}\right) \qquad C_{SDD} = 12.08\text{Mdol}$$

+ Ship test and evaluation

$$C_{STE} := 1.3\cdot\left(.499\cdot\frac{C_{FSB}}{F} + .647\cdot C_{I.MPG}\right) \qquad C_{STE} = 11.44\text{Mdol}$$

= ***Total Ship R&D Cost:***

$$C_{RD} := C_{SDD} + C_{STE} \qquad C_{RD} = 23.52\text{Mdol}$$

b) Investment (less base facilities, unrep, etc)

Ships:

$$C_{SPE} := \frac{C_{FA}}{F}\cdot N_S^{\frac{\ln(2\cdot R_L)}{\ln(2)}} \qquad C_{SPE} = 0.11\,\text{Bdol}$$

average ship cost: $C_{AVG} := \frac{C_{SPE}}{N_S}$ $\qquad C_{AVG} = 18.14\,\text{Mdol}$

+ Support Equipment (shore-based)

ship: $C_{SSE} := .15\cdot C_{SPE}$ $\qquad C_{SSE} = 0.02\,\text{Bdol}$

+ Spares and repair parts (shore supply)

ship: $C_{ISS} := .1\cdot C_{SPE}$ $\qquad C_{ISS} = 0.01\,\text{Bdol}$

= **Total Investment Cost** :

$$C_{INV} := C_{SPE} + C_{SSE} + C_{ISS}$$

$$C_{INV} = 0.14\ \text{Bdol}$$

+ **Operations:**

Operating hours/year: $H := 2500 \cdot hr$

$$C_{OPS} := N_S \cdot L_S \cdot \left[F_I \cdot Kdol \cdot \left[188. + 2.232 \left(N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{26.9 \cdot hr} \right] + \frac{C_{AVG}}{769.2} + \frac{C_{FMPG}}{196} \right]$$

$C_{OPS} = 0.04 Bdol$

+ **Maintenance**

$$C_{MTC} := N_S \cdot L_S \cdot \left[F_I \cdot Kdol \cdot \left[1967 + 4.114 \left(N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{3.05 \cdot hr} \right] + \frac{C_{AVG}}{156.25} \right]$$

$C_{MTC} = 0.43 Bdol$

MTC

+ **Energy (Assumes all operation at Endurance Power with no electric load)**

Fuel Rate:

$FR \cdot P_{eBAVG} = 10.96 \frac{lton}{hr}$

$C_{FUEL} := .9 \cdot \frac{dol}{gal}$

$$C_{EGY} := N_S \cdot L_S \cdot C_{FUEL} \cdot \frac{H}{6.8 \cdot \frac{lb}{gal}} \cdot FR \cdot P_{eBAVG}$$

$C_{EGY} = 1.71 Bdol$

+ **Replenishment Spares**

$$C_{REP} := C_{ISS} \cdot \frac{L_S - 4}{4}$$

$C_{REP} = 0.08 Bdol$

+ **Major Support (COH, ROH):**

$$C_{MSP} := N_S \cdot L_S \cdot \left[698. + 5.988 \left(N_{C_1} + N_{C_2} + N_{C_3} \right) - \frac{H}{10.36 hr} \right] \cdot Kdol \cdot F_I + .0022 C_{AVG}$$

$C_{MSP} = 0.16 Bdol$

= ***Total Operation and Support Cost:***

$$C_{OAS} := C_{PERS} + C_{OPS} + C_{MTC} + C_{EGY} + C_{REP} + C_{MSP}$$

$C_{OAS} = 2.43 Bdol$

d. Residual Value:

$$RES := .5 \cdot C_{SPE} \cdot \left(1 - \frac{2}{L_S} \right)^{L_S}$$

$RES = 0.01 Bdol$

e. Total Program

* ***Total Life Cycle Cost (Undiscounted):***

$$C_{LIFE} := C_{RD} + C_{INV} + C_{OAS} - RES$$

$C_{LIFE} = 2.58 Bdol$

7. Discounted Life Cycle Cost:

Discount Rate: $R_D := .1$

a. Discounted R&D:

Length of R&D Phase: $L_{RD} := 8$

end: $E_{RD} := Y_{IOC} + 2 - Y_B$ $\quad E_{RD} = 18$ **(normalized to base year)**

start: $B_{RD} := E_{RD} - L_{RD} + 1$ $\quad B_{RD} = 11$

$$F_{DRD} := \frac{\displaystyle\sum_{y = B_{RD}}^{E_{RD}} \frac{1}{(1 + R_D)^y}}{L_{RD}} \qquad F_{DRD} = 0.26$$

$C_{DRD} := F_{DRD} \cdot C_{RD}$ $\quad C_{DRD} = 6.05\text{Mdol}$

b. Discounted Investment

start: $B_{INV} := E_{RD} + 1$

end: $E_{INV} := B_{INV} + \text{ceil}\left(\left(\frac{N_S - 1}{R_P}\right)\right)$ $\quad E_{INV} = 24$

$L_{INV} := E_{INV} - B_{INV} + 1$ $\quad L_{INV} = 6$

$$F_{DINV} := \frac{\displaystyle\sum_{y = B_{INV}}^{E_{INV}} \frac{1}{(1 + R_D)^y}}{L_{INV}} \qquad F_{DINV} = 0.13$$

$C_{DINV} := F_{DINV} C_{INV}$ $\quad C_{DINV} = 0.02\text{Bdol}$

c. Discounted O&S

start: $B_{OAS} := E_{INV} + 1$ $\quad B_{OAS} = 25$

end: $E_{OAS} := B_{OAS} + L_S - 1$ $\quad E_{OAS} = 59$

$L_{OAS} := E_{OAS} - B_{OAS} + 1$ $\quad L_{OAS} = 35$

$$F_{DOAS} := \frac{\displaystyle\sum_{y=B_{OAS}}^{E_{OAS}} \frac{1}{(1+R_D)^y}}{L_{OAS}} \qquad F_{DOAS} = 0.03$$

$$C_{DOAS} := F_{DOAS} C_{OAS} \qquad C_{DOAS} = 0.07\text{Bdol}$$

d. Discounted Residual Value:

$$RES_D := RES\left(\frac{1}{1+R_D}\right)^{E_{OAS}+1} \qquad RES_D = 0.02\text{Mdol}$$

e. Total Discounted Life Cycle Cost:

$$C_{DLIFE} := C_{DRD} + C_{DINV} + C_{DOAS} - RES_D \qquad C_{DLIFE} = 91.7\text{Mdol}$$