Selection of Composite Materials for the Construction of Large Ships

by

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ABSTRACT

During last decades the use of composite materials in the shipbuilding industry has increased significantly, but still there is not any ship over 130 ft in length built with composites. Moreover, the availability of composite materials has been increased, resulting a similar decrease in their cost, as well as an improvement in their properties. So, it is the time for shipbuilders to consider incorporating composite structural materials in the design of large ships..

In this analysis, an optimum combination of composite materials was selected as the initial baseline for designing a large ship. The analysis was based in similar design concepts as for steel ships, but a different design concept was also proposed for further analysis. For all these structural analysis, MAESTRO© software from Proteus Engineering was used.

The analysis showed that a combination of graphite and glass based composites have adequate structural properties for manufacturing large ships with the minimum cost increase.

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1 Introduction

During the last few decades the use of composite materials has increased significantly due to their superior properties compared to conventional materials, as well as due to the reduction in their cost. New and improved fabrication techniques and higher demand has contributed to this cost reduction.

The marine industry has used composite materials since the mid 1960's, with its use limited to smaller size naval or merchant ships. The largest ship that has been built completely with composite materials is the 600 tonnes Swedish Visby class corvette. Use of composite materials for larger ships has not taken place due to the higher inherent risks and cost. Except for the reduction in cost, improvements in fabrication technologies have resulted in the appearance of new and better composites for the marine industry. Perhaps use of a combination of low and high-end composite materials would make it possible for the shipbuilding industry to proceed to the construction of larger ships without a significant increase in cost.

This thesis examines which combination of low and high-end composites could be used for the construction of larger ships with an objective of maximizing the reduction in structural weight and minimizing the increase in cost. For the analysis, a direct substitution of the structural elements of a steel hull with composite materials was considered. After the selection of the optimum material combination, an alternative design concept was considered for a further improvement.

The first part of the thesis includes the latest developments in the use of composite materials for the marine industry. The second part contains the assumptions that were used for the analysis, as well as basic laminate theory for composite materials. The third part reports the experimental optimization and the analysis of the results. Finally, the results from the alternative design concept will be shown.

This analysis was based on the material properties. Other areas of interest, like processing and machining methods for composites, mechanical fastening and adhesive bonding, as well as environmental effects and fire tolerance were not taken under consideration.

2 Background

Composites are becoming an essential part of today's materials because they offer advantages such as low weight, corrosion resistance and high fatigue strength. Composites are used as materials in making a wide variety of manufactured goods. These applications include aircraft structures, golf clubs, electronic packaging, medical equipment, space vehicles and home building.

A composite is a structural material that consists of combining two or more constituents. The constituents are combined at a macroscopic level and not soluble in each other. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers. The advantage of composite materials is that, if well designed, they usually exhibit the best qualities of their constituents and often some qualities that neither constituent possesses [Ref. 1]. Some properties that can be improved by forming a composite material are:

- Strength
- Stiffness
- Corrosion and wear resistance
- Weight
- Fatigue life.

2.1 Marine Applications of Composite Materials

The use of composite materials for marine applications started shortly after World

War II. Among the first applications was a series of 28 foot U.S. Navy personnel boats constructed with fiberglass [Ref. 2 - Ref. 3]. Since then many other boats have been constructed by the use of Fiber Reinforced Plastics (FRP) for recreational, commercial and military applications.

2.1.1 Recreational Applications

Fiberglass construction has been the mainstay of the recreational boating industry since the mid 1960's. After about 20 years of development work, manufacturing seized the opportunity to mass-produce easily maintained hulls with a minimum number of assembled parts. Much of the early FRP structural design work relied on trial and error, which may have also led to the high attrition rate of start-up builders. Current leading edge manufacturing technologies are driven by racing vessels, both power and sail [Figure 1, Ref. 3].

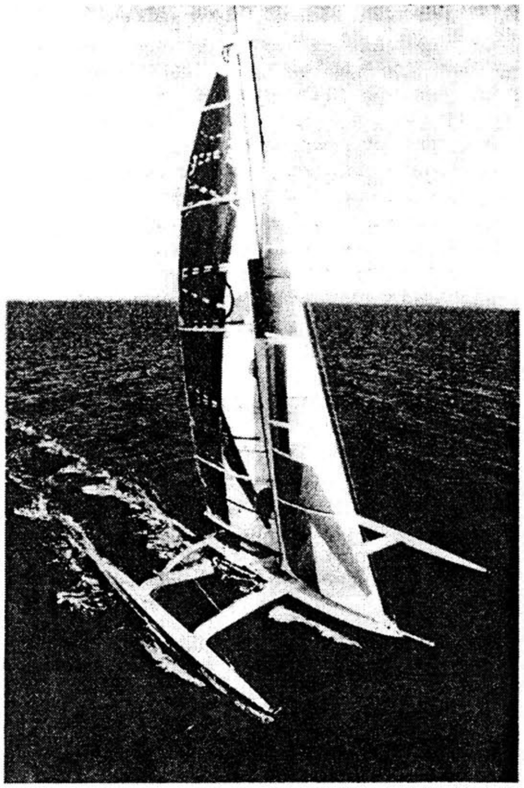

Figure 1: High performance racing trimaran Steinlager 1

From the 1950's to the 1980's, advances in materials and fabrication techniques used in the pleasure craft industry have helped to reduce production costs and improve product quality. Although every boat builder employs unique production procedures that they feel are proprietary, general industry trends can be traced over time as illustrated in Figure 2 [Ref. 3].

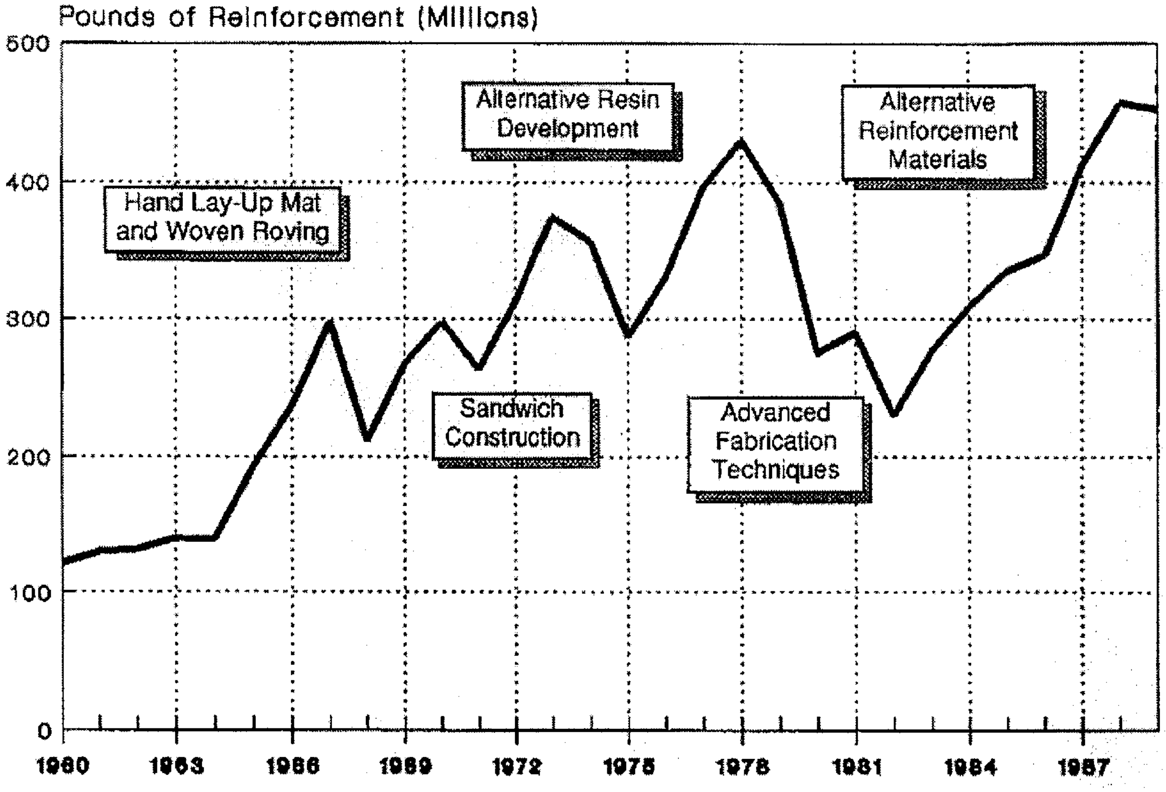

Figure 2: Annual shipment of reinforced thermoset and thermoplastic resin composites for the marine industry with associated construction developments.

2.1.1.1 Single-Skin Construction

Early fiberglass boat building produced single-skin structures with stiffeners to maintain reasonable panel sizes. Smaller structures used isotropic chopped strand mat layed-up manually or with a chopper gun. As strength requirements increased, fiberglass cloth and woven roving were integrated into the laminate. An ortho-polyester resin, applied with rollers, was almost universally accepted as the matrix material of choice.

2.1.1.2 Sandwich Construction

In the early 1970's, designers realized that increasingly stiffer and lighter structures could be realized if a sandwich construction technique was used. By laminating an inner and outer skin about a low-density core, reinforcements are located at a greater distance from the panel's neutral axis. These structures perform exceptionally well when subjected to bending loads produced by hydrodynamic forces. PVC foam and end-grain balsa have evolved as the primary core materials.

2.1.1.3 Resin Development

General-purpose ortho-polyester laminating resins still prevail throughout the boating industry due to its low cost and ease of use. However, boat builders of custom and higher-end craft have used a variety of other resins that exhibit better performance characteristics. Epoxy resins have long been known to have better strength properties than polyesters. Their high cost has limited use to only the most specialized of applications. Iso-polyester resin has been shown to resist blistering better than ortho-polyester resin and some manufacturers have switched to this entirely or for use as a barrier coat. Vinyl ester resin has performance properties somewhere between polyester and epoxy, exceeding epoxy in some respects, and has recently been examined for its excellent blister resistance. Cost is greater than polyester but less than epoxy.

2.1.1.4 Unidirectional and Stitched Fabric Reinforcement

The boating industry was not truly able to take advantage of the directional strength properties associated with fiberglass until unidirectional and stitched fabric reinforcements became available. Woven reinforcements, such as cloth or woven roving, have the disadvantage of "pre-buckling" the fibers, which greatly reduces in-plane strength properties.

Unidirectional reinforcements and stitched fabrics that are actually layers of unidirectional fibers offer superior characteristics in the direction coincident with the fiber axis. Pure unidirectional is very effective in longitudinal strength members such as stringers or along hull centerlines. The most popular of the knitted fabrics is the 45° by 45° knit which exhibits superior shear strength and is used to strengthen hulls torsionally and to tape-in secondary structure.

2.1.1.5 Advanced Fabrication Techniques

Spray-up with chopper guns and hand lay-up with rollers are the techniques that have endured for 30 years. In an effort to improve the components, some shops have adopted techniques to minimize voids. Thereby, improving production quality resulting in an increased fiber ratio. One technique involves placing vacuum bags with bleeder holes over the laminate during the curing process. This has the effect of applying uniform pressure to the skin and drawing out any excess resin or entrapped air. Another technique used to achieve consistent laminates involves using a mechanical impregnator that can produce 55% fiber ratios.

2.1.1.6 Alternate Reinforcement Materials

The field of composites gives the designer the freedom to use various different reinforcement materials to improve structural performance over fiberglass. Carbon and aramid fibers have evolved as two high strength alternatives in the marine industry. Each material has its own advantages and disadvantages. Both are significantly more expensive than fiberglass but have created another dimension of options with regards to laminate design. Some low-cost reinforcement materials that have emerged lately include polyester and polypropylene, These materials combine moderate strength properties with high strain-to-failure characteristics.

2.1.2 Commercial Applications

The use of fiberglass construction in the commercial marine industry has flourished over time for a number of different reasons. Initially, long-term durability and favorable fabrication economics were the impetus for using FRP. More recently, improved vessel performance through weight reduction has encouraged its use. Since the 1960's, manufacturers fabricated multiple vessels from the same mold. This significantly reduced the cost of FRP construction and made it more attractive [Ref. 3]. Following are some various sectors of the commercial market.

2.1.2.1 Fishing Industry

Although the production of commercial vessels has tapered off drastically, there was much interest in FRP trawlers during the early 1970's. The vessels that are still in service provide testimony to the reduced long-term maintenance claims which led to their construction. For example, the 55-foot *POLLY ESTER* has been in service in the North Sea since 1967. Shrimp trawlers were the first FRP fishing vessels built in the U.S.A. with the *R.C. BRENT,* launched in 1968. In 1990, commercial fishing fleets were approximately 50% FRP construction [Ref. 3]. Other aspects of FRP construction that appeal to this industry include increased hull life, reduction in hull weight and cleaner fish holds. Despite the increase in the number of fishing vessels, the fishing industry has been conservative in adopting GRP for larger hulls (LOA>25m).

2.1.2.2 Larger Passenger and Cargo Vessels

The use of composite materials for passenger and cargo vessels of over 40m length is not competitive with steel because of the increased cost. Some exceptions are high-performance crafts, like commercial hovercrafts [Ref. 4]. The biggest yacht constructed by sandwich composite is *Evivva*, which was launched in July 1994 by Admiral Marine in Port Townsend, Washington [Ref. 6].

In 1971, the Ship Structure Committee published a detailed report entitled "Feasibility Study of Glass Reinforced Plastic Cargo Ship" [Ref. 5]. A 470-foot, dry/bulk cargo vessel was chosen for evaluation whereby engineering and economic factors were considered. Some of the conclusions of this study at that time were:

- The general conclusion was that the design and fabrication of a large GRP cargo ship was shown to be totally within the present state-of-the-art, but the long-term durability of the structure was questionable.
- The most favorable laminate studied was a woven-roving/unidirectional composite, which proved 43% lighter than steel but had 20% of the stiffness.
- GRP structures for large ships could not meet U.S. Coast Guard fire regulations and significant economic incentive would be necessary to pursue variants.
- Cost analyses indicated unfavorable required freight rates for GRP versus steel construction in all but a few of the sensitivity studies.
- Major structural elements such as deckhouses, hatch covers, king posts and bow modules appeared to be very well suited for GRP construction.
- Commercial vessels of the 150-250 foot size appeared to be more promising than the vessels studied and deserve further investigation.

2.1.3 Military Applications

Composite materials have advantages that are very attractive for military applications. Composites allow an integration of a number of survivability requirements and have beneficial material characteristics. Polymer composites also have excellent ballistic properties, yet are considerably lighter than equivalent steel armor plate. Properly prepared composite materials are nearly impervious to the corrosive effects of the ocean environment, resulting in reduced maintenance. Finally, the ability of composites to provide low magnetic signature and stealth are two very important characteristics for combatant ships [Ref. 7]. Because of these additional advantages, there is a great effort from the navies around the world to build even larger structures. Until recently, the use of composite materials for larger ship (LOA>40m) was limited to Mine Countermeasure Vessels (MCM). The largest ship build totally by composite materials was the Hunt-Class in the United Kingdom, with a total overall length of 60m. In 1996, the Swedish Navy started the construction of the Visby-Class corvette. The launch date is scheduled for June 2000 [Ref. 8], and it will be the largest ship build totally by composite materials with an overall length of 71m and 600 tonnes displacement [Ref. 9].

2.2 Structural Concepts

Composite marine vessels are generally constructed using one of the four following design concepts [Ref. 10]:

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

The first two concepts are similar as for the construction of recreational vessels. Table 1 [Ref. 4-Ref. 11-Ref. 12-Ref. 13] shows recent and current MCM construction with the corresponding method of construction.

Type	**Country**	**Hull Construction**
Wilton	UK	Single Skin GRP
Hunt Class	UK	Single Skin GRP
Sandown Class	UK	Single Skin GRP
Tripartite	Netherlands, France, Belgium	Single Skin GRP
Lerici Class	Italy	Unstiffened monocoque GRP
Osprey Class	USA	Unstiffened monocoque GRP
Landsort Class	Sweden	PVC-core Sandwich GRP
Visby	Sweden	PVC-core Sandwich Graphite - Vinyl Ester
Bay Class	Australia, Norway	PVC-core Sandwich GRP
BAMO Class	France	Single Skin GRP hull, balsa-core sandwich deck
Huon Class	Australia	Unstiffened monocoque GRP
Segura Class	Spain	Single Skin monocoque GRP with longitudinal stiffeners in the base and transverse along the sides.

Table 1: Recent and current MCM construction

Monocoque single-skin construction creates panel structures that span across the turn of the bilge to the hull-to-deck joint and extend from bow to stern. Very thick skins are required to make this construction method feasible for anything but the smallest vessels. It is interesting to observe that the Osprey class minehunter design [Figure 3, Ref. 11], which was commissioned in 1993, and the Huon Class design [Figure 4, Ref. 12] that was commissioned in 1999, are also monocoque.

Figure 3: MHC-53 Pelican - Osprey Class minehunter

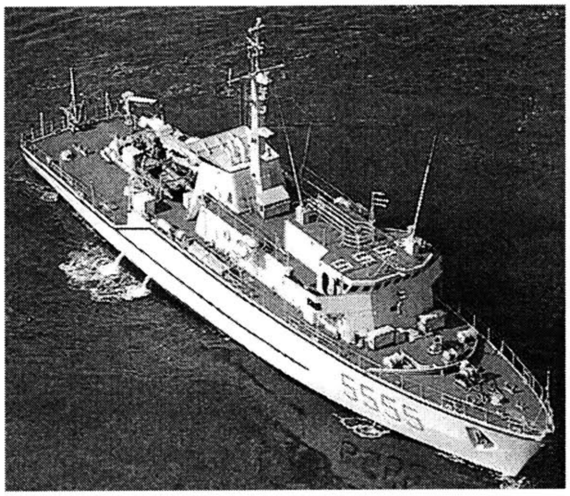

Figure 4: HMAS Huon – Huon Class minehunter

Single-skin construction is more often combined with a system of bulkheads and stringers to reduce the effective panel spans, and thus reduce the laminate strength and stiffness necessary. Figure 5 [Ref. 4] shows the design concept for a transversely framed single-skin construction for a hull section. The latest constructed minehunter with this concept is the Spanish Segura Class, which was commissioned in November 1998, and can be seen in Figure 6 [Ref. 13].

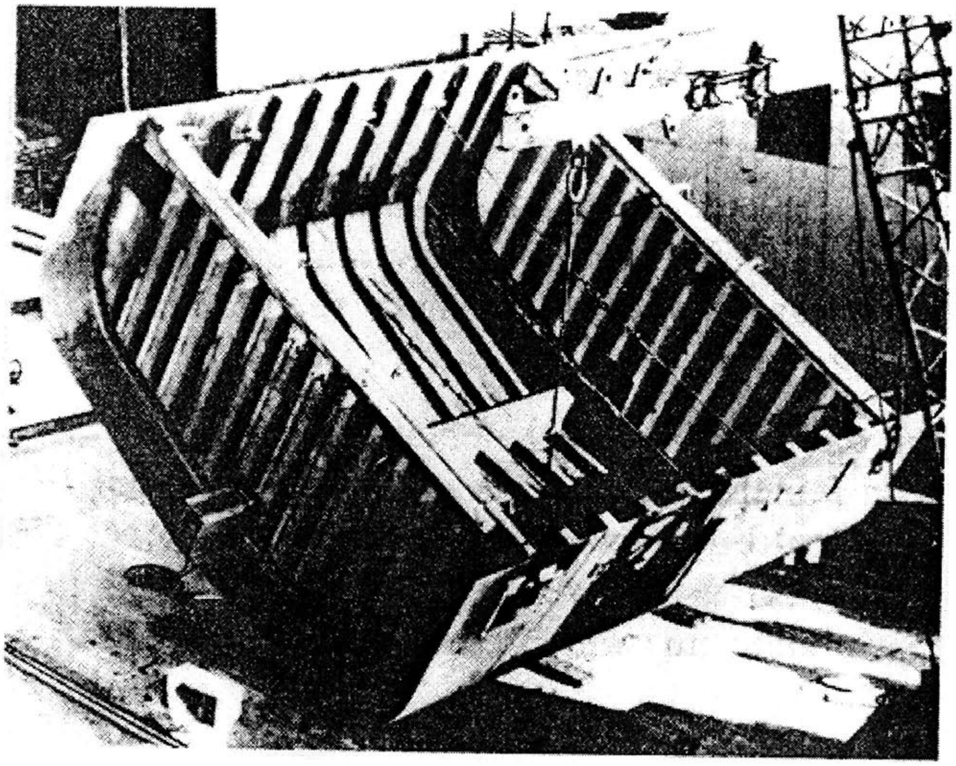

Figure 5: Transversely framed hull section

Figure 6: Segura M31 – Segura Class minehunter

Sandwich laminates can resist loads over large spans, while at the same time possess sufficient overall longitudinal stiffness contribution to alleviate the need for added longitudinal stiffeners. Sandwich construction that makes use of bulkheads and stringers permits the use of softer skin and core materials. Panel spans are reduced compared to single-skin construction, although stiffener spacing is typically much greater because the thick sandwich laminate has inherently higher moments of inertia. The Visby-Class corvette [Figure 7, Ref. 8] follows this concept. The hull material is a sandwich construction comprising a PVC core with a carbon fiber and vinyl laminate. The material provides high strength and rigidity, low weight, good shock resistance, low radar signature and low magnetic signature. The manufacture of the flat panels uses a vacuum injection process. The panels are then joined to form larger hull sections.

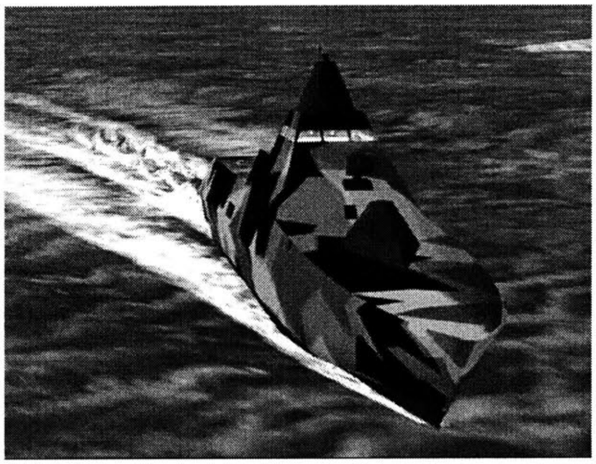

Figure 7: Visby Class corvette

2.3 Materials

The constituents of composite materials can be separated to three categories [Ref. 10]:

- Reinforcements
- Resins
- Core materials

Glass fibers account for over 90% of the fibers used in reinforced plastics, because they are inexpensive to produce and have relatively good strength to weight characteristics.

Additionally, glass fibers exhibit good chemical resistance and processability. Reinforcements for marine composite structures are primarily E-Glass due to its cost for strength and workability characteristics. In contrast, the aerospace industry relies on carbon fibers. In general, carbon and aramid fibers and other specialty reinforcements are used in the marine field where structures are highly engineered for optimum efficiency.

The marine industry has generally based its structures on polyester resin, with trends to vinyl ester and epoxy for structurally demanding projects and highly engineered products. A particular resin system is effected by formulation, additives, catylization, and cure conditions.

Core materials form the basis for sandwich composite structures, which clearly have advantages in marine construction. A core is any material that can physically separate strong, laminated skins and transmit shearing forces across the sandwich. Core materials range from natural species, such as balsa and plywood, to highly engineered honeycomb or foam structures. The dynamic behavior of a composite structure is integrally related to the characteristics of the core material used.

2.4 The Potential of Composite Materials

In many respects the potential applications for composite materials are limitless because of the variety of materials which will become available. Twenty years ago, fibers-reinforced composites barely existed. Commercialization of carbon fibers changed that. In the 1980s the use of composites was widespread and widely accepted. Initially, military aircraft designers accepted much of the cost of developing and characterizing the materials, and the civil market has followed. The future can only be one of increased composite usage. It is, however, important to grasp what composite materials will encompass [Ref. 14].

Composites in the form of fiber-reinforced plastics were developed and introduced initially into aircraft in order to give weight savings over aluminum alloys. These savings could be equated to reduced fuel consumption or increased payload. This is now an oversimplification, as one generation of composites replaces another. Composites are now exploited to provide an accumulation of benefits with an emphasis on lowering production and lifetime costs. In the following paragraphs the most recent developments in fibers and resins will be discussed.

2.4.1 Carbon fiber development

The aircraft industry is seeking fibers with higher strain to failure, to increase design strength allowable, and help improve damage tolerance. The figures in Table 2 [Ref. 14] show this trend. In order to utilize these improved properties, new polymeric matrices of equivalent failure are required.

Fiber	**Generation**	**Young Modulus (Gpa)**	**Tensile Strength (Gpa)**	**Strain to Failure %**
Toray T300	1st	235	3530	1.5
Courtaulds XAS	1st	235	3100	1.3
Courtaulds Apollo HS	2nd	245	5000	2.0
Toray T800	2nd	294	5586	1.9
Hercules IM7	2nd	303	5518	1.86

Table 2: Basic properties of 1st and 2nd generation fibers

2.4.2 Aramid and other fiber developments

Aramid fibers have enjoyed considerable success in applications requiring very high tensile strength to weight coupled with modest stiffness. Kevlar 149 is now offered with a higher modulus and lower inherent moisture absorbency characteristics.

2.4.3 Polymer matrix developments

Composites remain structurally efficient provided the matrix is integrated with the fibers. Epoxies can achieve this in the temperature range –50 °C to +130 °C. At elevated temperatures of 200 °C and beyond, which are increasingly required of aircraft structures, other types of thermosets are required, i.e. bismaleimides and plyimides. These matrices have their own problems in terms of brittleness and high temperature curing, but these can be solved. Thermoplastic matrices such as polyetheretherketone (PEEK) are gaining prominence because of the following inherent characteristics; improved matrix toughness, hydrolytic stability and repeatable thermoformable characteristics. Many of these new matrices are being combined with the improved fibers.

2.4.4 Metal matrix composite (MMC) development

The main difference between metal and polymer based composites is that any metal matrix is a structural material in its own, whereas a polymer matrix is not. This confers on a metal matrix composite inherently higher interlaminar, transverse, compressive and shear properties coupled with higher thermal stability. The initial obstacles to overcome with MMC technology center on fiber and matrix compatibility and cost-effective manufacturing techniques.

2.4.5 High temperature refractory composites

In the future there will be a need for composites capable of operating at 800 °C and beyond. This requirement will be centered on engines and power plants. To meet these goals carbon fiber-reinforced carbon (C – C), glass matrix composites and ceramic matrix composites will provide the solutions. Of these, C – C composites are more commercially advanced but require elaborate oxidation protection systems. Glass and ceramic matrix composites require considerable development in the areas of fiber/matrix compatibility and adaptable manufacturing techniques to achieve acceptable mechanical properties both in terms of strength and toughness.

2.4.6 The adaptability of composite materials

One of the main characteristics of composites is the freedom available to designers to optimize the material composition to provide solutions to structural needs. Examples include:

1. Radar transparent domes made of glass or quartz fiber-reinforced plastics. Conversely it is also possible to modify carbon and kevlar fiber composites to make them radar absorptive.

2. Properly designed fiber-reinforced plastic structures have the ability to absorb large amounts of impact energy and provide increased crashworthiness.

3. Materials are often expected to perform multiple tasks. An example is a smart material, in which sensors embedded in the material are used to determine conditions within the material. The use of an embedded sensor to define real-time conditions in a structure is beneficial in predicting critical component life, or identifying when preassigned parameters reach a critical stage and require specific action. One approach to developing smart structures is to use fiber optics embedded in a composite. They can directly embedded into the structure during manufacture and are somewhat protected from damage [Ref. 15].

2.5 Selection of a Naval Ship

The use of composite materials for the construction of small ships is presently fairly mature. For larger ships, a steel structure is still preferred, in part due to the perception that it is a cheaper design, and also in part due to a relative low level of experience with the use of composite materials on these ships. Technology in composite materials has significantly improved in recent years. The production cost has decreased, and will continue to do so even more if there is an increase in demand for such materials for the shipbuilding of larger ships. Perhaps now is the time to start considering making this big step towards the production of large composite naval structures and especially for military applications, since the composite materials offer many other advantages.

In order to evaluate the benefits of the use of composite materials for building large ships, a reference baseline hull design was selected for evaluation and comparison. The selected hull is the midship section of a DDG ship. The principle characteristics of that hull can be found in Table 3. Moreover, Figure 8 shows the mid-ship section for a DDG and Figure 9 shows the panel segments and node points of the mid-ship as derived from the U.S. Navy Advanced Surface Ship Evaluation Tool (ASSET). Finally, the structural geometry details can be found in Appendix 1.

Length Between Perpendiculars	466 ft	Prismatic Coefficient	0.615
Length Overall	492.06 ft	Max Section Coefficient	0.822
Beam	59 ft	Waterplane Coefficient	0.791
Beam at Weather Deck	66.45 ft	Light Ship Displacement	6686 lton
Draft	20.69 ft	Full Load Displacement	8672 lton
Depth at Station 10	41.83 ft	Hull Structure Weight	2100 lton

Table 3: Hull principal dimensions (on design waterline)

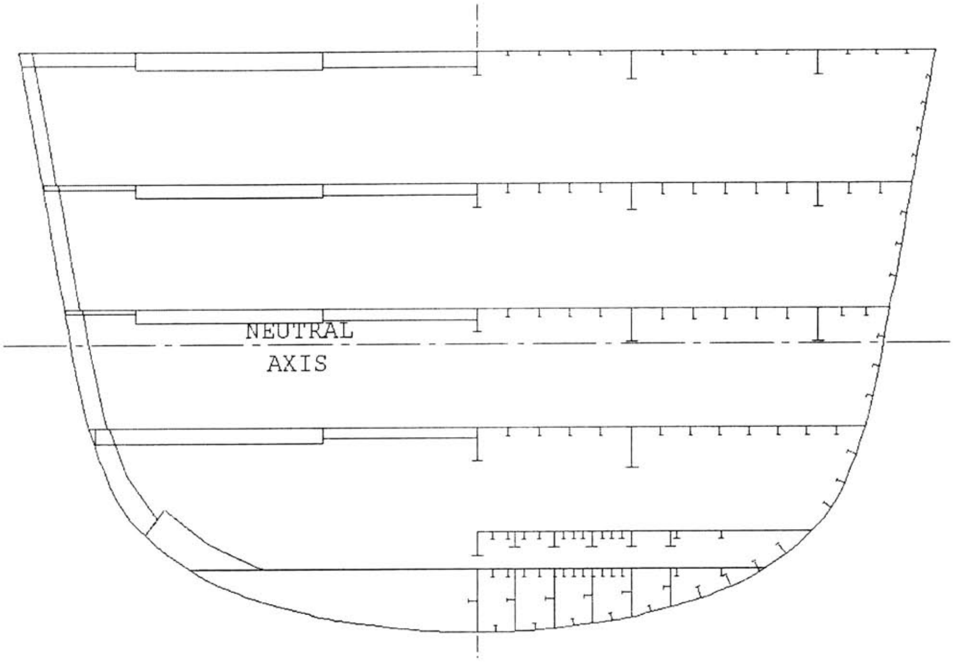

Figure 8: Mid-Ship Section – DDG

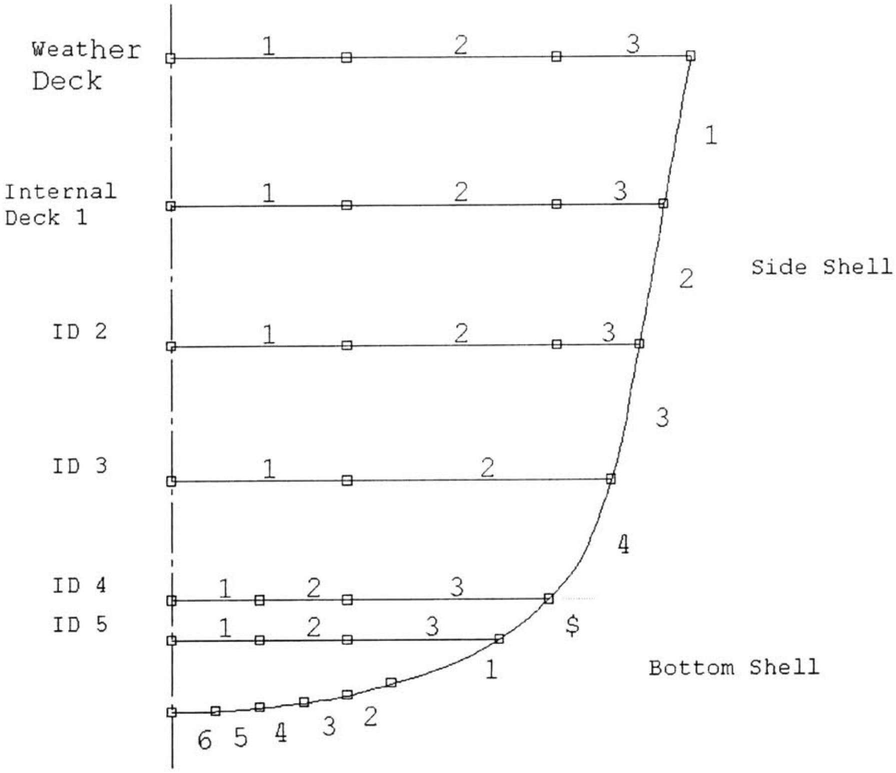

Figure 9: Mid-ship panels segments and node points.

2.5.1 Loads

For the structural analysis and optimization, the following loads were considered:

- Hogging and sagging bending moments (primary hull loads) according the equation:

$$BM_{hog} = -0.000457 \cdot L^{2.5} \cdot B \qquad \text{(Equ. 1)}$$

$$BM_{sag} = 0.000381 \cdot L^{2.5} \cdot B \qquad \text{(Equ. 2)}$$

Where L is the length of the ship in ft and B is the beam of the ship in ft. The units for the bending moments are in $lton \cdot ft$.

- Hydrostatic pressure of 6m, (secondary hull loads) equal to the draft of the ship.
- 2.72 ft of water height for simulating the live loads on all decks (tertiary deck loads).
- 4 ft of water height on the weather deck for simulating green seas (tertiary deck loads).
- 7 ft of water height on the side panels for simulating slamming (tertiary deck loads).

3 Materials

3.1 Constituents of Composite Materials

Ultimate strength, stiffness, density and other physical properties of laminates fabricated for ship structure, are very much dependent upon the constituent materials, the orientation and arrangement of these materials, and the manufacturing process used. Consequently, there is a wide range of alternatives available for fabrication. Many of the fabrication parameters involved have a significant effect on the cost of the ship structure and must be evaluated in terms of cost and benefit to achieve an optimum ship of superior structure at a cost comparable to, or below that of metal alternatives. The constituent materials are the resins and fibers.

3.1.1 Resins

The principal types of resin used in FRP marine structures are listed, along with their main properties, in Table 4 [Ref. 16]. The most commonly used resin is orthophthalic polyester. This resin typically has the lowest cost, but at the expense of low performance. Epoxy and vinyl ester resins are preferred for applications that require high strength, toughness and stiffness. Moreover, epoxies possess superior abrasion resistance, less water absorption, and greater bonding strength. Phenolic resins have poor strength characteristics, but are used for thermal and fire protection. [Ref. 5, Ref. 16, Ref. 17]

3.1.2 Fibers

The principal types of fibers used in FRP marine structures, along with their main characteristics, are listed in Table 5 [Ref. 16]. E-Glass is the most commonly used fiber material. S-Glass is used where higher strength is required. Aramid ranks among the highest in specific strength, but suffers from poor compression strength. It is most used for high impact areas, especially in armor plating. Carbon fibers offer the highest stiffness of the materials listed, but it is more brittle than kevlar, and has the problem of being corrosive when bonded to aluminum. A combination of carbon or aramid fibers with E-Glass is often used as an intermediate compromise among strength, stiffness and cost. [Ref. 16, Ref. 17]

Resins	Density (lb/ft^3)	Tensile Strength (ksi)	Tensile Modulus (ksi)	Material Cost ($/lb) (1996)
Orthophthalic Polyester	76.7	7	5.9	0.7
Isophthalic Polyester	75.5	10.3	5.7	0.8
Phenolic	71.8	5.1	5.3	0.8
Epoxy	74.9	7.9	5.3	2.8
Vinyl Ester	69.9	11.0	4.9	1.5

Table 4: Resin Characteristics

Fibers	Density (lb/ft^3)	Tensile Strength (ksi)	Tensile Modulus (ksi)	Ultimate Elongation (%)	Material Cost ($/lb) (1996)
E-Glass	162.4	500	10.5	4.8	1.0
S-Glass	155.5	665	12.6	5.7	4.0
Aramid (Kevlar)	90.0	525	18.0	2.9	20.0
Carbon (Graphite)	109.7	700	57.0	0.4	2.0

Table 5: Fiber Characteristics

3.2 Material Costs

Material selection should consider material and maintenance cost. Discussions regarding materials for construction to date have centered on the relationship of cost to weight savings, using traditional aluminum constructions as a basis and comparing various fiberglass reinforced plastic / composite / resin systems. Of interest at this point is the relationship between structural weight savings and the use of higher cost, more "advanced" fiberglass reinforced plastic composite materials and their techniques for construction. This will create a weight metric that can be traded at the system level for more payload or fuel, or less power at a reduced cost for similar speed.

Table 6 [Ref. 18] shows the results of materials cost per pound study from Ref. 18. The raw cost of each material includes reinforcement fabrics plus resin. The raw costs *(RC)* of materials are rationalized to a dollar per kilogram basis and averaged from a variety of industry sources including manufacturers, builders and materials suppliers. The application efficiency *(AE)* column is generated from materials suppliers and boatbuilder's input. The application cost *(AC)* for each material is generated from the standardized labor rate *(SLR)* of \$50.00 U.S. per hour divided by the application efficiency in kilograms per hour. Finally, the total cost *(TC)* is determined by combining raw cost/pound and application cost/pound.

$$AC = \frac{SLR}{AE} \quad \text{and} \quad TC = AC + RC \qquad \text{(Equ. 3)}$$

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

Table 6: Cost comparison of various materials

3.3 Resins and Fibers Selection

3.3.1 Resin Selection

The most popular resins used in the marine industry and which will be analyzed further in this study are the epoxy and vinyl ester, since they provide high strength, toughness and stiffness.

3.3.1.1 Epoxy Resins

Epoxy resin systems have achieved acceptance as adhesives, potting compounds, and molding compounds and as matrices for continuous filament composites used in structural applications. As matrices in fiber composites, they possess several advantages over other types of polymers. These main advantages are:

- Inherently polar nature that confers excellent adhesion to a wide variety of fibers.
- Relatively low cure shrinkage that makes dimensional accuracy of fabricated structures easier to obtain.
- No volatile by-products of the curing reaction to cause undesired bubble or void formation.
- Crosslinked structure that confers excellent resistance to hostile environments, both aqueous and non-aqueous

In addition to these advantages, epoxy resins have tremendous versatility because they can be formulated to meet a broad range of specific processing and performance requirements.

3.3.1.2 Vinyl Ester Resins

Vinyl ester resins are the most recent addition to the family of thermosetting polymers. Although several types of these resins were synthesized in small quantities during the late 1950s, it was not until the mid-1960s that commercialization led the push to establish this extremely important segment of today's composite industry. Vinyl esters are unsaturated resins made from the reaction of unsaturated carboxylic acids with an epoxy such as a bisphenol A epoxy resin. The structure of vinyl ester resins shows several important features that account for the resultant exceptional properties of vinyl ester resins. There is an epoxy resin backbone with a high molecular weight that provides excellent mechanical properties combined with toughness and resilience. Secondly, vinyl esters display terminal unsaturation, which makes them very reactive. They can be dissolved in styrene and cured like conventional unsaturated polyester to give rapid strength. Finally, vinyl esters have much fewer ester linkages per molecular weight that combined with the acid resistant epoxy backbone, giving outstanding chemical resistance to this class of resins.

3.3.2 Fiber Selection

All type of fibers have been used in specific applications. Each combination of resin and fiber has its own characteristics and properties, and it is best for a specific use. The most popular fibers for marine applications are graphite and glass fibers.

3.3.2.1 Graphite fibers

Graphite fibers exhibit truly outstanding properties. Their strength competes with the strongest steel. They can have stiffness greater than any metal, ceramic or polymer; and they can exhibit thermal and electrical conductivities that greatly exceed those of competing materials. The strength or stiffness values combined with the low density, results in high specific properties making this class of materials quite unique.

3.3.2.2 Glass fibers

Glass fibers are the most commonly used fibers. The continuing widespread use of glass fibers in numerous and diverse applications can be directly related to its inherent unique properties, which are:

- High tensile strength: Glass fibers have an exceptionally high tensile strength compared with other textile fibers. Its strength to weight ratio exceeds steel wire in some applications.
- Heat and fire resistance: Because fiberglass is inorganic it does not burn or support combustion.
- Chemical resistance: Glass fibers have excellent resistance to most chemicals and are impervious to fungal, bacterial or insect attack.
- Moisture resistance: Because glass fibers do not absorb water, they neither swell, stretch nor disintegrate. Glass fibers do not readily rot and continue to maintain its mechanical strength in humid environments.
- Thermal properties: Due to its low coefficient of thermal linear expansion and high coefficient of thermal conductivity, glass fibers exhibit excellent performance in thermal environments.

3.4 Composite Materials Selection

For the evaluation of composite materials for the construction of a large ship, the following combinations of fibers and resins will be considered:

1. Fiber: Graphite Resin: Epoxy

2. Fiber: Graphite Resin: Vinyl Ester
3. Fiber: Glass Resin: Epoxy
4. Fiber: Glass Resin: Vinyl Ester

S-Glass will be used for the glass fibers, since they provide the highest strength among the different glass fiber types.

4 Material Properties

4.1 Stress – Strains Relations for Anisotropic Materials

The generalized Hooke's law relating stresses to strains can be written in contracted notations as Ref. 19:

$$\sigma_i = C_{ij} \cdot \varepsilon_j = \sum_{j=1}^{6} C_{ij} \cdot \varepsilon_j \qquad \text{i, j} = 1,\dots,6 \qquad \text{(Equ. 4)}$$

where σ_i are the stress components shown on a three-dimensional cube in x, y, z coordinates, C_{ij} is the stiffness matrix, and ε_j are the strains components. The contracted notation for three-dimensional stresses and strains is defined in comparison to the usual tensor notation in Table 7. The total number of constants is 36, but due to symmetry, for complete anisotropic materials the number of independent constants drop to 21. Once these constants are found for a particular point, the stress and stain relationship can be developed at that point.

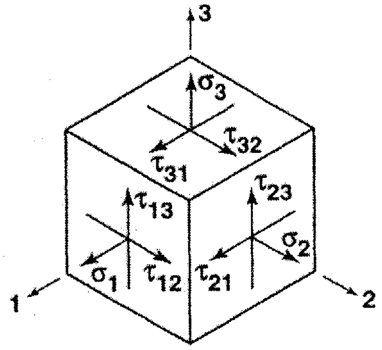

Figure 10: Stresses on an element

Stresses		Strains	
Tensor Notation	Contracted Notation	Tensor Notation	Contracted Notation
σ_{11}	σ_1	ε_{11}	ε_1
σ_{22}	σ_2	ε_{22}	ε_2
σ_{33}	σ_3	ε_{33}	ε_3
τ_{23}	σ_4	γ_{23}	ε_4
τ_{31}	σ_5	γ_{31}	ε_5
τ_{12}	σ_6	γ_{12}	ε_6

Table 7: Tensor versus contracted notations for stresses and strains

4.1.1 Other Type of Materials

4.1.1.1 Monoclinic materials

If there is one plane of material symmetry, then the stiffness matrix has 13 independent constants. The direction perpendicular to the plane of symmetry is called the "principal direction". Equation 5 gives the complete stiffness matrix for a monoclinic material.

$$[C]=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ C_{12} & C_{22} & C_{23} & 0 & 0 & C_{26} \\ C_{13} & C_{23} & C_{33} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{44} & C_{45} & 0 \\ 0 & 0 & 0 & C_{45} & C_{55} & 0 \\ C_{16} & C_{26} & C_{36} & 0 & 0 & C_{66} \end{bmatrix} \qquad \text{(Equ. 5)}$$

4.1.1.2 Orthotropic material

If a material has three mutually perpendicular planes of material symmetry, then the stiffness matrix has 9 independent constants. This is the most common type of composite material. The complete stiffness matrix for an orthotropic material is:

$$[C]=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad \text{(Equ. 6)}$$

4.1.1.3 Transversely isotropic materials

If an orthotropic material has one plane of isotropy then it is been called transversely isotropic and has 5 independent elastic constants. The complete stiffness matrix for a transversely isotropic material is:

$$[C]=\begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{12} & C_{23} & C_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{C_{22}-C_{23}}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{bmatrix} \quad \text{(Equ. 7)}$$

4.1.1.4 Isotropic material

If all planes in an orthotropic body are identical, it is an isotropic material; then the stiffness matrix has only two independent constants, which are the C_{11} and C_{12}. The complete matrix is:

$$[C]=\begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{C_{11}-C_{12}}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{C_{11}-C_{12}}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{C_{11}-C_{12}}{2} \end{bmatrix} \qquad \text{(Equ. 8)}$$

In this case the required properties are two of the following:

- Young modulus (E)
- Shear modulus (G)
- Poisson ratio (v), since:

$$C_{11}=\frac{\mathrm{E}\cdot(1-\nu)}{(1-2\cdot\nu)\cdot(1+\nu)},\ C_{12}=\frac{\nu\cdot\mathrm{E}}{(1-2\cdot\nu)\cdot(1+\nu)}\ \text{and}\ G=\frac{C_{11}-C_{12}}{2}=\frac{\mathrm{E}}{2\cdot(1+\nu)} \qquad \text{(Equ. 9)}$$

4.2 Ship Structure Loads

Hull structure loading is typically referred to as primary, secondary and tertiary, as noted in Figure 11 [Ref. 10]. Primary are the overall hull bending moments, secondary are the hydrostatic and hydrodynamic forces normal to hull surface, and tertiary are the local loads.

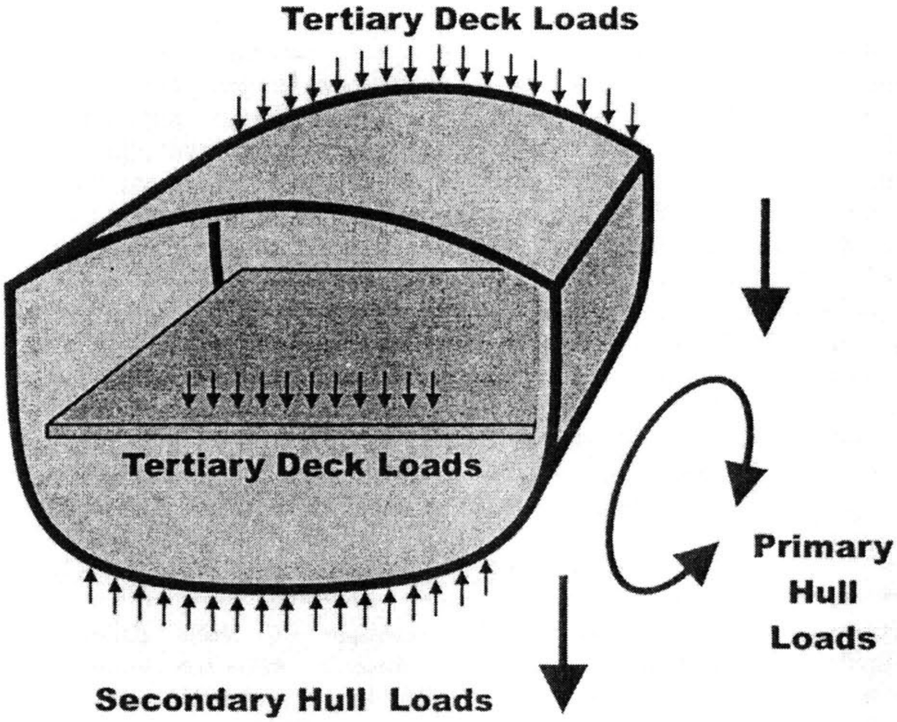

Figure 11: Overview of primary, secondary and tertiary loads

For the structural analysis of the midship section that has been selected, two software programs were considered, MAESTRO© and NASTRAN©. The advantage of NASTRAN© is that it has a very powerful code for handling finite elements with composite materials. On the other hand, it has the disadvantage that the elements must be very small, and so it is very difficult to model structures as large as a ship module, and it needs much more computational time for the analysis. MAESTRO© software requires that the materials used for the analysis be isotropic or orthotropic. It also has capabilities for handling composite materials, although somewhat limited. Moreover, the modeling of large structures, especially marine structures, is easier since the code is designed mainly for such applications. For the last two reasons, it was decided that the MAESTRO© software would be used for the analysis.

The three basic properties required by MAESTRO© are: Young's modulus, Poisson's ratio and yield strength of the material. Under certain simplifications the composite materials that have been selected for the structural elements of the ship can be considered as isotropic or orthotropic, and the effective values of the material properties can be used. In the following paragraphs these assumptions are analyzed for the different structural elements.

4.3 Material Properties for Stiffeners, Girders, Frames

The structural loads result in mainly axial stresses on the girders, stiffeners and frames, both compressive and tensile. It can be assumed that the analysis is only in one dimension. A general unidirectional composite material is orthotropic, so, if the resulting stresses are only on one axis, then the composite can be considered as isotropic along this axis. For that reason, stiffeners, girders and frames as composites with unidirectional only fiber were considered. The corresponding properties for the epoxy-based resins were taken from experimental results according Ref. 28 and they can be seen in Table 8 [Ref. 28].

Property	Graphite/ Epoxy	Glass/ Epoxy
Axial Young's Modulus (GPa)	181	38.6
Transverse Young's Modulus (GPa)	10.3	8.27
Poisson's Ratio	0.28	0.26
Shear Modulus (GPa)	7.17	4.14
Longitudinal Tensile Strenght (MPa)	1500	1062
Longitudinal Compressive Strenght (MPa)	1500	610
Transverse Tensile Strength (MPa)	40	31
Transverse Compressive Strength (MPa)	246	118
Shear Strength (MPa)	68	72
Specific Gravity	1.62	2.11

Table 8: Experimental results for the epoxy based composites

Similar experimental results for the vinyl ester based resins were not available. They were calculated by using the micromechanical analysis of laminate theory as explained analytically in the following paragraphs [Ref. 1].

4.3.1 Density

The derivation of the density of the composite in terms of volume fractions is found as follows:

$$\rho_c = \rho_f \cdot V_f + \rho_m \cdot V_m \qquad \text{(Equ. 10)}$$

Where: ρ_c, ρ_f and ρ_m are the densities for the composite, the fiber and the matrix respectively.

V_f and V_m are the volume fraction for the fiber and matrix respectively.

4.3.2 Longitudinal Young's Modulus

The derivation of the longitudinal Young's Modulus of the composite is found as follows:

$$E_{Lc} = E_{Lf} \cdot V_f + E_{Lm} \cdot V_m \qquad \text{(Equ. 11)}$$

Where: E_{Lc}, E_{Lf} and E_{Lm} are the Young's Modulus for the composite, the fiber and the matrix respectively.

4.3.3 Transverse Young's Modulus

The transverse Young's Modulus is calculated by:

$$E_{Tc} = \left(\frac{V_f}{E_{Tf}} + \frac{V_m}{E_{Tm}} \right)^{-1} \qquad \text{(Equ. 12)}$$

4.3.4 Poisson's Ratio

The major Poisson is ratio is calculated by:

$$\nu_c = \nu_f \cdot V_f + \nu_m \cdot V_m \qquad \text{(Equ. 13)}$$

Where: ν_c, ν_f and ν_m are the Poisson's ratios for the composite, the fiber and the matrix respectively.

4.3.5 In-Plane Shear Modulus

The equation for the in-plane shear modulus G_c is:

$$G_c = G_m \cdot \left(\frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \right) \qquad \text{(Equ. 14)}$$

where: ξ is the reinforcing factor and $\xi = 1 + 40 \cdot V_f^{10}$ and

$$\eta = \frac{\left(G_f / G_m \right) - 1}{\left(G_f / G_m \right) + \xi}$$

4.3.6 Longitudinal Tensile Strength

The longitudinal tensile strength is:

$$\sigma_{LT} = \sigma_{Lf} \cdot V_f + \varepsilon_{L_f} \cdot \varepsilon_{Lm} \cdot (1 - V_f) \qquad \text{(Equ. 15)}$$

where: ε_{Lf} is the longitudinal failure strain of the fiber and $\varepsilon_{Lf} = \frac{\sigma_{Lf}}{E_f}$

ε_{Lm} is the longitudinal failure strain of the matrix and $\varepsilon_{Lm} = \frac{\sigma_m}{E_m}$

4.3.7 Longitudinal Compressive Strength

There are two failure modes for calculating the longitudinal compressive strength, the Shear/Extensional fiber microbuckling failure mode and the Shear Stress failure of fibers mode. Due to first failure mode there is:

$$S_1^c = 2 \cdot \left[V_f + (1 - V_f) \cdot \frac{E_{Lm}}{E_{Lf}} \right] \cdot \sqrt{\frac{V_f \cdot E_{Lm} \cdot E_{Lf}}{3 \cdot (1 - V_f)}} \qquad \text{(Equ. 16)}$$

$$S_2^c = \frac{G_m}{1 - V_f} \qquad \text{(Equ. 17)}$$

Where S_1^c is the extensional mode buckling stress and

S_2^c is the shear mode buckling stress

Due to the second failure mode there is:

$$S_3^c = 2 \cdot (S_f \cdot V_f + S_m \cdot V_m) \qquad \text{(Equ. 18)}$$

Where S_f and S_m are the shear strength of the fiber and the matrix respectively.

The longitudinal compressive strength then is:

$$\sigma_{Lc} = \min\left[S_1^c, S_2^c, S_3^c\right] \qquad \text{(Equ. 19)}$$

4.3.8 Transverse Tensile Strength

For the transverse tensile strength it is necessary to calculate first the transverse tensile strain. There are two empirical formulas:

$$\varepsilon_{T1} = \varepsilon_{Tm} \cdot \left(1 - V_f^{1/3}\right) \qquad \text{(Equ. 20)}$$

$$\varepsilon_{T2} = \varepsilon_{Tm} \cdot \left[\sqrt{\frac{4 \cdot V_f}{\pi}} \cdot \left(\frac{E_{Tm}}{E_{Tf}} - 1 \right) + 1 \right] \qquad \text{(Equ. 21)}$$

By choosing the minimum of equation 20 and 21 ($\varepsilon_T = \min[\varepsilon_{T1}, \varepsilon_{T2}]$) it is possible to calculate the transverse tensile strength by:

$$\sigma_{Tt} = E_{Tc} \cdot \varepsilon_T \qquad \text{(Equ. 22)}$$

4.3.9 Transverse Compressive Strength

A similar equation can be used for the calculation of the transverse compressive strength.

$$\sigma_{Tc} = E_T \cdot \varepsilon_C \qquad \text{(Equ. 23)}$$

Where: $\varepsilon_C = \left[\sqrt{\frac{4 \cdot V_f}{\pi}} \cdot \frac{E_{Tm}}{E_{Tf}} + \left(1 - \sqrt{\frac{4 \cdot V_f}{\pi}} \right) \right] \cdot \frac{\sigma_{Cm}}{E_{Tm}}$

4.3.10 Shear Strength

Finally, for the Shear Strength of ply it is:

$$S = G_C \cdot \left(\sqrt{\frac{4 \cdot V_f}{\pi}} \cdot \frac{G_m}{G_f} + \left(1 - \sqrt{\frac{4 \cdot V_f}{\pi}} \right) \right) \cdot \frac{S_m}{G_m} \qquad \text{(Equ. 24)}$$

4.4 Properties of Vinyl Ester Based Composites

Using basic laminate theory, the properties of the vinyl ester based composites were calculated by the use of the corresponding properties of the fibers and resin as found in Table

9. For these calculations, a Matlab code was written, which is in Appendix 2. For comparison reasons, the properties of the epoxy-based composites were also calculated and compared with the experimental one as in Table 10.

Property	Graphite	Glass	Epoxy	Vinyl Ester
Axial Young's Modulus (GPa)	230	85	3.4	3.38
Transverse Young's Modulus (GPa)	22	85	3.4	3.38
Poisson's Ratio	0.3	0.2	0.3	0.3
Shear Modulus (GPa)	22	35.42	1.31	3.1
Longitudinal Tensile Strength (MPa)	2067	1550	72	82.74
Longitudinal Compressive Strength (MPa)	1999	1550	102	117.2
Transverse Tensile Strength (MPa)	77	1550	72	82.74
Transverse Compressive Strength (MPa)	42	1550	102	117.2
Shear Strength (MPa)	36	35	34	12.41
Specific Gravity	1.8	2.5	1.2	1.12

Table 9: Properties of fibers and resins that were used during the calculation of the properties for the composites.

Property	Graphite	Glass	Graphite	Glass
	Experiment		Theory	
Axial Young's Modulus (GPa)	181	38.6	162	60.52
Transverse Young's Modulus (GPa)	10.3	8.27	8.33	10.37
Poisson's Ratio	0.28	0.26	0.3	0.23
Shear Modulus (GPa)	7.17	4.14	7.06	4.01
Longitudinal Tensile Strength (MPa)	1500	1062	1456	1103
Longitudinal Compressive Strength (MPa)	1500	610	70.8	69.4
Transverse Tensile Strength (MPa)	40	31	12.33	20.57
Transverse Compressive Strength (MPa)	246	118	50.43	29.14
Shear Strength (MPa)	68	72	20.6	9.5
Specific Gravity	1.62	2.11	1.62	2.11

Table 10: Comparison of the experimental and theoretical properties of the epoxy based composites

From this comparison we can see that the theory could not accurately predict the longitudinal compressive strength, the transverse strength and the shear strength. The difference in compressive strength between the experimental results and the theoretical ones are factors of ten to twenty. From this observation, it was concluded that it was not appropriate to use the exact theoretical calculated values for the vinyl ester based composites in the process of the material selection. Since more accurate values for these properties were not available, it was decided to use a correction factor for the theoretical calculated properties equal to the corresponding ratios between the experimental and theoretical results for the epoxy based composites. Table 11 provides the final used properties for the vinyl ester based composites with a direct comparison with the theoretical calculated values.

Property	Graphite	Glass	Graphite	Glass
	Theory		Corrected	
Axial Young's Modulus (GPa)	162	60.51	181	38.6
Transverse Young's Modulus (GPa)	8.29	10.31	10.25	8.23
Poisson's Ratio	0.3	0.23	0.28	0.26
Shear Modulus (GPa)	7.78	8.6	7.9	8.86
Longitudinal Tensile Strength (MPa)	1456	1103	1500	1062
Longitudinal Compressive Strength (MPa)	57.85	56.45	1225	496
Transverse Tensile Strength (MPa)	14.17	23.6	46	35.56
Transverse Compressive Strength (MPa)	57.8	33.42	282	135.32
Shear Strength (MPa)	8.67	8	28.63	60.78
Specific Gravity	1.6	2.086	1.6	2.086

Table 11: Theoretical and corrected properties for vinyl ester based composites

For the analysis, since the loads on the girders, frames and stiffeners are axial, these materials can be considered isotropic for the longitudinal axis. MAESTRO$^{\copyright}$ requires as inputs for characterizing materials only three properties, moduli of elasticity, Poisson's ratio and longitudinal strength. With this assumption the selected materials have different compressive and tensile strengths. Since the resulting stresses in these structural elements due to the ship's structural loads are both compressive and tensile, in order to be conservative in the analysis, the lower strength was used. Table 12 shows the final material properties used as inputs for the girders, stiffeners and frames.

Fiber	Resin	Young's Modulus E (GPa)	Poisson Ratio v	Yield Strength (MPa)
Graphite	Epoxy	181	0.28	1500
Graphite	Vinyl-Ester	181	0.28	1225
Glass	Epoxy	38.6	0.26	610
Glass	Vinyl-Ester	38.6	0.26	496

Table 12: Material properties for the selected composite materials for the stiffeners, girders and frames.

4.5 Material properties for plates

Usually, composite materials are constructed as very thin plies. Plies can be considered as 2-D structures, since the thickness is much smaller than the other two dimensions. Moreover, if they are not heavily loaded in the thickness direction compared to the other two dimensions, we can assume σ_3, σ_4 and σ_5 stresses are much smaller than σ_1, σ_2 and σ_6 stresses. Under these assumptions – plane stress, for a single ply of an orthotropic composite material the Hooke's law in matrix format along the fiber axis reduces to:

$$[\sigma]=\begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}\cdot[\varepsilon] \qquad \text{(Equ. 25)}$$

with only four independent constants. In order to calculate these independent constants it is necessary to include all four properties of the ply. Transverse and longitudinal Young's modulus, shear modulus and Poisson's ratio.

When two or more plies are bonded and stacked one on top another to act as a single structural layered element, this structural element is called a layered laminate. A fiber reinforced plastic (FRP) laminate may have individual plies oriented at different angles relative to the reference axes, to produce the desired stiffness and strength in the required directions of the laminate. The properties of the layered laminate are, therefore, very much dependent on the individual ply properties and the stacking sequence, that is, the sequence in which individual plies are layered in a laminate. For a ship structure, a layered laminate corresponds to a plate [Ref. 21].

4.5.1 Calculations of equivalent material constants for a laminate

For this analysis it is required to have the equivalent material constants and strength of a laminate. These can be calculated from the engineering constants and strength of the plies that constitute the laminate. As has been mentioned previously, MAESTRO© software can accept isotropic or orthotropic properties. Under certain conditions, it is possible for a composite laminate to behave as an isotropic material. This happens in a quasi-isotropic composite laminate. A quasi-isotropic laminate is symmetric with respect to the cross sections of the laminate and is also balanced. Thus for every ply with positive angle, there is one with negative angle [Ref. 1, Ref. 19, Ref. 20, Ref. 21].

For a laminate, instead of using the stiffness matrix [Q], the extensional stiffness matrix [A] is used. The equation that relates [A] and [Q] matrices is:

$$[A]=\sum_{k=1}^{N}\left[\overline{Q}^{(k)}\right]\cdot t_k \qquad \text{Equ. 26}$$

where N is the total number of plies in the laminate, $\left[\overline{Q}\right]$ is the stiffness matrix for each ply with respect to the laminate coordinate system, and t_k is the thickness of each ply.

For a quasi-isotropic laminate, the extensional stiffness matrix [A] is:

$$[A]=\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{11} & 0 \\ 0 & 0 & \dfrac{A_{11}-A_{12}}{2} \end{bmatrix} \qquad \text{(Equ. 27)}$$

The stresses is related to strain as:

$$[\sigma]=[A]\cdot[\varepsilon] \ \Rightarrow\ [\varepsilon]=[\alpha]\cdot[\sigma] \text{ where } [\alpha]=[A]^{-1} \qquad \text{(Equ. 28)}$$

where $[\sigma]$ is the matrix of the applied stresses, and $[\varepsilon]$ are the resulting strains on the laminate. Assuming unit thickness for the laminate, the equivalent material constants for the quasi-isotropic laminate can be calculated by the following two equations:

$$E=\frac{1}{\alpha_{11}} \text{ and } \nu=\frac{\alpha_{12}}{\alpha_{11}} \qquad \text{(Equ. 29)}$$

Appendix 3 has the Matlab program for the calculation of these engineering constants.

4.5.2 Calculations of equivalent laminate strength

The analytical laminate strength can be predicted by two methods [Ref. 21]. The first is the complete ply failure approach and the second is the partial ply failure approach. Using either of the prediction methods, laminate analysis can be tedious. A faster method for estimating the laminate strength would be useful for initial design purposes.

A proposed method for estimating the laminate strength is based on the following reasoning: the total load carried by the laminate in a particular loading mode, i.e. tension, compression or shear, is the sum of the individual ultimate ply loads for the same loading mode. This reasoning assumes that there are no interactions between the plies, implying that the ply interface is not contributing to the load carrying capabilities of the laminate. The ultimate longitudinal tensile load carried by the laminate is, therefore, the summation of all the longitudinal loads carried by individual plies in tension.

The total laminate load is the ultimate laminate strength multiplied by the total laminate thickness, i.e. $N = F \cdot t$, where N is the ultimate load, F is the ultimate strength, and t is the laminate thickness. The total carried by an individual ply is $N_p = F_p \cdot t_p$, where the subscript ‘p’ denotes the ply. Thus the ultimate laminate strength is given by:

$$F \cdot t = \sum_{p=1}^{N} F_p \cdot t_p \qquad \text{(Equ. 30)}$$

4.5.3 Properties for Plates

In order for the plates to meet the above requirements, it was assumed that the plates were fabricated by symmetric and balanced laminates. The most common stacking sequence for an orthotropic composite is $[0/\pm45/90]_S$. The equivalent material constants for each type of material were calculated from equations 29 and 30, and can be found in Table 13. Finally, Appendix 3 provides the Matlab code that was used for these calculations.

Fiber	Resin	Young's Modulus E (Gpa)	Poisson Ratio v	Yield Strength (Mpa)
Graphite	Epoxy	69.68	0.296	425
Graphite	Vinyl-Ester	70.27	0.29	405.4
Glass	Epoxy	18.97	0.27	254
Glass	Vinyl-Ester	22.36	0.138	218.6

Table 13: Material properties for the selected composite materials for the plates

5 Optimization Method

The purpose of this analysis was to find the optimum material combination for each structural element of a ship in order to reduce the total weight and cost of the structure.

5.1 General Approach

The optimization method that was used for the selection of the optimum composite material for each structural element was the Taguchi method using orthogonal arrays [Ref. 24]. The orthogonal arrays are specially designed matrices of test conditions. The objective of orthogonal arrays is to determine a global optimum given a set of design parameters (factors) without resorting to full factorial experimentation. A full factorial count is the number of parameter settings raised to the power of the number of design parameters (factors). That is to say, six design parameters with five settings each, would require 15625 separate experiments for full factorial evaluation, while by the use of orthogonal arrays the total number would be only 25. In an orthogonal array, each value of each parameter is tested an equal number of times and each of these values is tested with every value of all the other parameters an equal amount of times.

In the Taguchi method, the results of the experiments are analyzed to achieve one or more of the following three objectives:

- To establish the best or the optimum condition for a product or a process
- To estimate the contribution of individual factors
- To estimate the response under the optimum conditions

The optimum condition is identified by studying the main effects of each of the factors. The process involves minor arithmetic manipulation of the numerical results. The main effects indicate the general trend of the influence of the factors. Knowing the characteristics, i.e., whether a higher or lower value produces the preferred result, the levels of the factors which are expected to produce the best results can be predicted.

The knowledge of the contribution of individual factors is a key to deciding the nature of the control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiment to determine the percent contribution of each factor. Study of the ANOVA table for a given analysis helps to determine which of the factors need control and which do not.

Once the optimum condition is determined, it is usually a good practice to run a confirmation experiment. It is, however, possible to estimate performance at the optimum condition from the results of experiments conducted at a non-optimum condition. It should be noted that the optimum condition may not necessarily be among the many experiments already carried out, as the orthogonal arrays represent only a small fraction of all the possibilities.

Taguchi suggests two different routes to carry out the complete analysis. First, the standard approach, where the result of a single run, or the average of repetitive runs, are processed through main effect and ANOVA analyses as identified above. The second approach is to use signal to noise (S/N) ratio for the same steps in the analysis. S/N analysis determines the most robust set of operating conditions from variations within the results.

5.2 Design of the Experiment

For the present optimization problem we wanted to find the best material for each structural elements of the ship in an overall structural design. The main structural elements for a ship or the factors of the experiment are:

1. Plates

2. Stiffeners

3. Longitudinal Girders

4. Transverse Frames

There are four possible materials that define the levels of the materials that were compared during the optimization process.

1. Graphite / Epoxy

2. Graphite / Vinyl-Ester

3. Glass / Epoxy

4. Glass / Vinyl-Ester

For designing a ship, weight and cost are the two most important factors. If it desired just to minimize weight, then a composite with Graphite fibers should be used, since they have the higher specific strength [Table 14]. Alternatively, if the lowest cost is most desirable, then a composite with just glass fibers should be selected. These results can also be seen graphically in Figure 12 and Figure 13.

Material	Strength (MPa)	Modulus (GPa)	Specific Gravity	Cost ($/kg)
Glass/Vinyl-Ester	496	38.6	2.08	14.13
Graphite/Vinyl-Ester	1225	181	1.6	26
Glass/Epoxy	610	38.6	2.11	15.26
Graphite/Epoxy	1500	181	1.62	28.08

Material	Specific Strength	Specific Stiffness	S. Strength / Cost	S. Stiffness / Cost
Glass/Vinyl-Ester	238.46	18.56	16.88	1.31
Graphite/Vinyl-Ester	765.63	113.13	29.45	4.35
Glass/Epoxy	289.10	18.29	18.94	1.20
Graphite/Epoxy	925.93	111.73	32.97	3.98

Table 14: Specific Strength and Specific Strength over Cost Ratio Comparison for Graphite and Glass Composites.

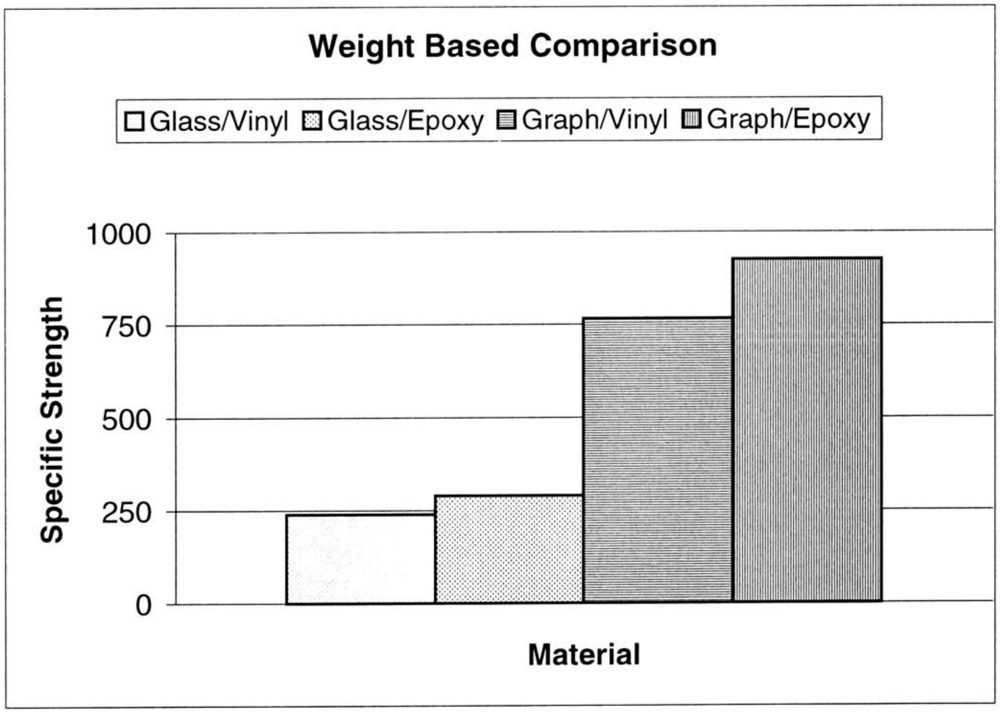

Figure 12: Weight based comparison

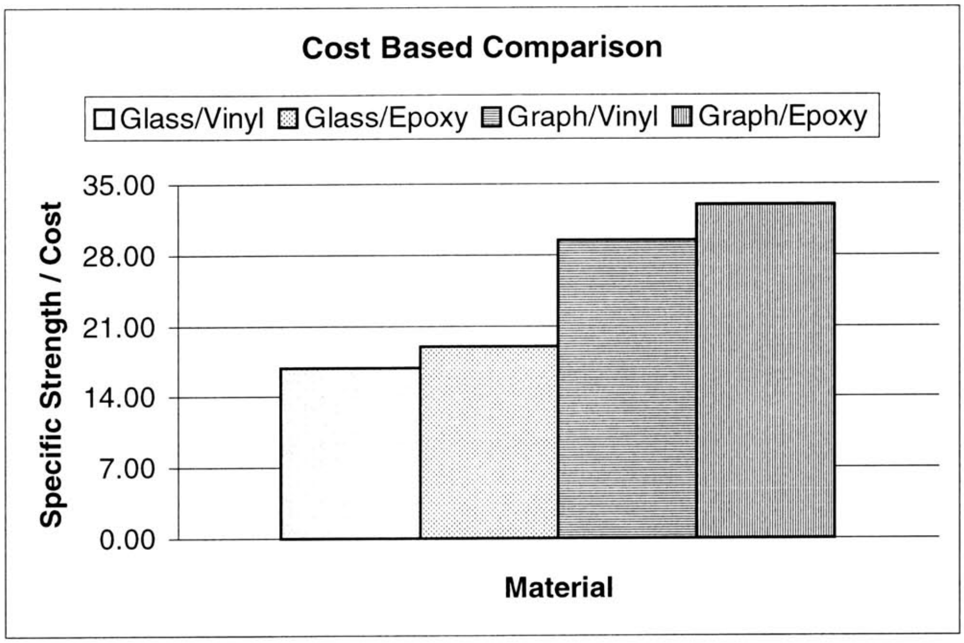

Figure 13: Cost based comparison

5.2.1 Objective Function

For the present analysis, a selection of materials is desired that will minimize an objective function based on both weight and cost. The objective function that was used was the following:

$$\lambda_1 \cdot W + \lambda_2 \cdot C = \min \qquad \text{(Equ. 31)}$$

where λ_1 and λ_2 are the coefficients for weight and cost respectively and $\lambda_1 + \lambda_2 = 1$. For the present analysis, both these coefficients were considered equal to 0.5, but these factors can be changed depending the requirements for each case.

For this optimization, the total number of factors is four (the number of the structural elements), and the total number of levels is again four (the number of the different materials). The degrees of freedom, or the number of experiments that have to be conducted to estimate the effect of each factor is sixteen. Table 15 shows the different experiments that were considered.

Experiment Number	Plate Material	Frame Material	Girder Material	Stiffener Material
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	1	2	3	4
6	2	1	4	3
7	3	4	1	2
8	4	3	2	1
9	1	3	4	2
10	2	4	3	1
11	3	1	2	4
12	4	2	1	3
13	1	4	2	3
14	2	3	1	4
15	3	2	4	1
16	4	1	3	2

Table 15: Orthogonal Array for the Present Optimization Problem

Where: Level 1 → Graphite / Epoxy
Level 2 → Graphite / Vinyl-Ester
Level 3 → Glass / Epoxy
Level 4 → Glass / Vinyl-Ester

6 Structural Analysis

MAESTRO© was used for the structural analysis and structural optimization of each of the previous defined alternatives. The purpose of this structural optimization is discussed in the following paragraph and was used for all the experiments.

For the structural analysis and structural optimization, a 14.24m long model of the Auxiliary Machinery Room was modeled in MAESTRO© as seen in Figure 14. For a reference baseline, a steel structure was initially analyzed and optimized. After having an optimum steel design the different experiments were also optimized.

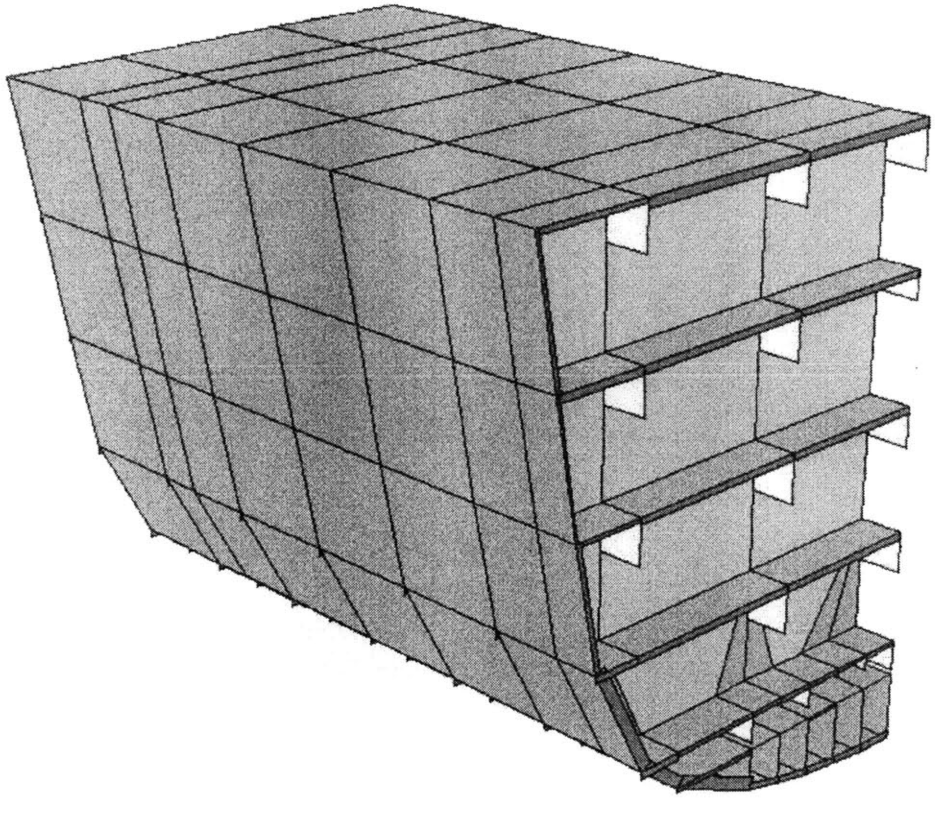

Figure 14: MAESTRO© Model

6.1 Structural Optimization

The purpose of each structural optimization was to find the best scantling sizes for each material configuration that would minimize the total weight of the structure. An optimum design was achieved when all the resulting adequacy parameters from the structural analysis were positive. A problem that was faced during the structural optimization of each of the configurations was that the optimization method that MAESTRO© uses is not very robust. It needs regular intervention from the user. The theory on which the structural optimization method that MAESTRO© uses and the way the code works can be found in Ref. 26 and Ref. 27 respectively. The outputs from these optimization runs were the sizes of the scantlings. With the use of an EXCEL spreadsheet, the weight and cost of each individual scantling was calculated for each material configuration. The total weight and cost resulting from each experiment were tabulated for the analysis. These results can be found in Table 16. For the calculation of the objective function, the weight and cost of the composite structures have been nondimensionilized by the corresponding weight and cost of the steel structure.

Experiment Number	Weight (Kg)	Cost ($)	Objective F.
1	65291	2023609	0.959
2	64599	1853828	0.887
3	121071	2039258	1.062
4	128693	2007088	1.062
5	85368	2353458	1.131
6	81724	2132950	1.033
7	159555	3189833	1.609
8	157909	3019983	1.536
9	79086	1998760	0.972
10	78409	1934210	0.944
11	165077	3001371	1.540
12	163845	2914034	1.502
13	94626	2638249	1.266
14	97567	2541075	1.231
15	120391	2166403	1.114
16	122569	2101921	1.091

Steel Weight:	288380
Steel Cost:	1196777

Table 16: Experiment Results

From an initial comparison between the results from the different experiments and the steel structure, it can be noticed that there is a significant weight savings by the use of any composite material compared to steel. On the other hand, composite structures have higher cost.

After having these results, the Taguchi minimization method was used for the optimization analysis. Three different analyses were conducted, minimizing the total structural weight, minimizing the total cost and finally minimizing the objective function. For the optimization the first step was to calculate the signal-to-noise ratio for each experiment and for each result. This ratio combines the loss effects attributable to both missing a target and having too large a variation about that target:

$$S/N = \eta = -10 \cdot \log_{10}(result^2) \qquad \text{(Equ. 32)}$$

The Signal-to-Noise ratio for each experiment can be seen in the following Table 17.

Experiment Number	S/N(weight)	S/N(cost)	S/N(Obj.F.)
1	-96.30	-126.12	0.37
2	-96.20	-125.36	1.05
3	-101.66	-126.19	-0.52
4	-102.19	-126.05	-0.52
5	-98.63	-127.43	-1.07
6	-98.25	-126.58	-0.28
7	-104.06	-130.08	-4.13
8	-103.97	-129.60	-3.73
9	-97.96	-126.02	0.25
10	-97.89	-125.73	0.50
11	-104.35	-129.55	-3.75
12	-104.29	-129.29	-3.53
13	-99.52	-128.43	-2.05
14	-99.79	-128.10	-1.80
15	-101.61	-126.71	-0.94
16	-101.77	-126.45	-0.75
Mean	**-100.63**	**-127.46**	**-1.41**

Table 17: Signal-to-Noise Ratios for each experiment

The second step for the analysis was the calculation of the main effect of each factor at each level:

$$m_{f_x} = \frac{1}{n_{f_x}} \cdot \sum \eta_{(\text{exp. w/factor "f" and setting "x"})} \qquad \text{(Equ. 33)}$$

where: m_{fx} is the main effect of the factor "f" at level "x" and

n_{fx} is the total number of experiments.

For each optimization analysis a different table resulted [Table 18]. The highest main effect for each factor corresponds to the material with the most affect in minimizing the weight, cost and the objective function correspondingly. For the optimum signal to noise ratio we have:

$$\eta_{opt} = m + \sum \left(m_{f_x} - m\right) \qquad \text{(Equ. 34)}$$

Where: m is the mean value of the signal to noise ratio and

m_{f_x} is the best setting for each factor summed

One other important parameter that the analysis of the variances provides is the relative importance of a factor in the final solution. The higher the relative importance of the factor, the most the level of this factor affects the optimum signal to noise ratio. For calculating the relative importance of a factor we have:

$$\sum_f SQ = \sum_{i=1}^{n_x} n_{f_x} \cdot (m_{f_x} - m)^2 \qquad \text{(Equ. 35)}$$

Where: $\sum_f SQ$ is called the factor "f" sum of squares,

n_{f_x} is the number of experiments with factor "f" and setting "x" and

m_{f_x} is the main effect of experiments with factor "f" and setting "x"

So, the percentage of the relative importance is given by the following equation:

$$\%Rel.Imp._f = \frac{\sum_f SQ}{\sum_{i=1}^{4}\left(\sum_i SQ\right)} \qquad \text{(Equ. 36)}$$

From the optimum signal to noise ratio, it is possible to predict the optimum response:

$$opt.response = 10^{\left(\eta/_{-20}\right)} \qquad \text{(Equ. 37)}$$

These results found analytically for each process are shown in the following Table 18.

	Minimize Weight						
	m_{fx}						
Factors	**Graph/Epoxy**	**Graph/Vinyl-Ester**	**Glass/Epoxy**	**Glass/Vinyl-Ester**	**Σ Sq**	**% Rel. Imp.**	**$(m_f - m)$**
Plate's Material	-98.10	***-98.03***	-102.92	-103.05	96.92	89%	2.50
Frame Material	***-100.17***	-100.18	-100.84	-100.91	2.00	2%	0.36
Girder Material	-101.11	-101.01	***-99.99***	-100.00	4.56	4%	0.54
Stiffener Material	***-99.94***	-100.00	-100.93	-101.24	5.17	5%	0.59
				Total	108.64	100%	-96.54

Min Weight:
67169.09

	Minimize Cost						
	m_{fx}						
Factors	**Graph/Epoxy**	**Graph/Vinyl-Ester**	**Glass/Epoxy**	**Glass/Vinyl-Ester**	**Σ Sq**	**% Rel. Imp.**	**$(m_f - m)$**
Plate's Material	-127.00	***-126.44***	-128.13	-127.85	7.22	29%	0.91
Frame Material	***-127.18***	-127.20	-127.48	-127.57	0.47	2%	0.18
Girder Material	-128.40	-128.23	-126.45	***-126.34***	14.82	61%	1.02
Stiffener Material	-127.04	***-126.98***	-127.62	-127.78	1.98	8%	0.38
				Total	24.49	100%	-124.87

Min Cost:
1751388.29

	Minimize Objective Function						
	m_{fx}						
Factors	**Graph/Epoxy**	**Graph/Vinyl-Ester**	**Glass/Epoxy**	**Glass/Vinyl-Ester**	**Σ Sq**	**% Rel. Imp.**	**$(m_f - m)$**
Plate's Material	-0.63	***-0.13***	-2.34	-2.13	14.30	48%	1.17
Frame Material	***-1.10***	-1.12	-1.45	-1.55	0.62	2%	0.20
Girder Material	-2.28	-2.12	-0.46	***-0.37***	12.74	42%	0.93
Stiffener Material	-0.95	***-0.90***	-1.60	-1.79	2.43	8%	0.41
				Total	30.10	100%	2.72

Min Obj. F.:
0.73

Table 1: Main Effects of each factor for each level, where:
Level 1 → Graphite / Epoxy
Level 2 → Graphite / Vinyl Ester
Level 3 → Glass / Epoxy
Level 4 → Glass / Vinyl Ester

6.2 Optimal Design

Based on these results, the materials for each structural element for optimal design were:

Minimizing weight: Plates → Graphite / Vinyl Ester
Frames → Graphite / Epoxy
Girders → Glass / Epoxy
Stiffeners → Graphite / Epoxy

Minimizing Cost: Plates → Graphite / Vinyl Ester
Frames → Graphite / Epoxy
Girders → Glass / Vinyl Ester
Stiffeners → Graphite / Vinyl Ester

Minimizing O.F.: Plates → Graphite / Vinyl Ester
Frames → Graphite / Epoxy
Girders → Glass / Vinyl Ester
Stiffeners → Graphite / Vinyl Ester

And the predicted values were respectively:

- Minimum weight of 67,169 kg.
- Minimum Cost of $1,751,890 and
- Minimum Objective function of 0.73

7 Analysis of the Results

Based on the results of this evaluation, the recommended materials for minimizing the weight are not the expected ones. The materials for the scantlings for minimizing the structural weight should have graphite fibers and not glass fibers, since graphite fibers are both stronger and lighter than the glass fibers, as previously explained in section 6.1. On the other hand, the analysis showed that for the girders the Glass / Epoxy material should be used, despite the fact that the predicted minimum weight is higher than the second experiment. The reason for this discrepancy is the very big difference in the stiffness of the material and the limited ability of MAESTRO© for the optimization.

As can be seen in Figure 15, if there is a change in the material of the girder from Graphite / Epoxy to Glass / Epoxy, with the material of the plate-stiffener combination being Graphite / Epoxy, then there is a decrease in the stress concentration on the girder with a similar increase in the stress concentration on the plate. The opposite can be observed in Figure 16. In this comparison, the material of the girder changed from Glass / Vinyl-Ester to Graphite / Vinyl-Ester, with the material of the plate-stiffener combination being Glass / Vinyl-Ester. This time there is an increase in the stress concentration on the girders and a decrease on the plates. The reason for this change in the stress concentration is due to the difference in the stiffness between the graphite and glass fibers. The ratio of stress distribution between the girders and the plate-stiffener combination is the same as the ratio in their respective stiffness.

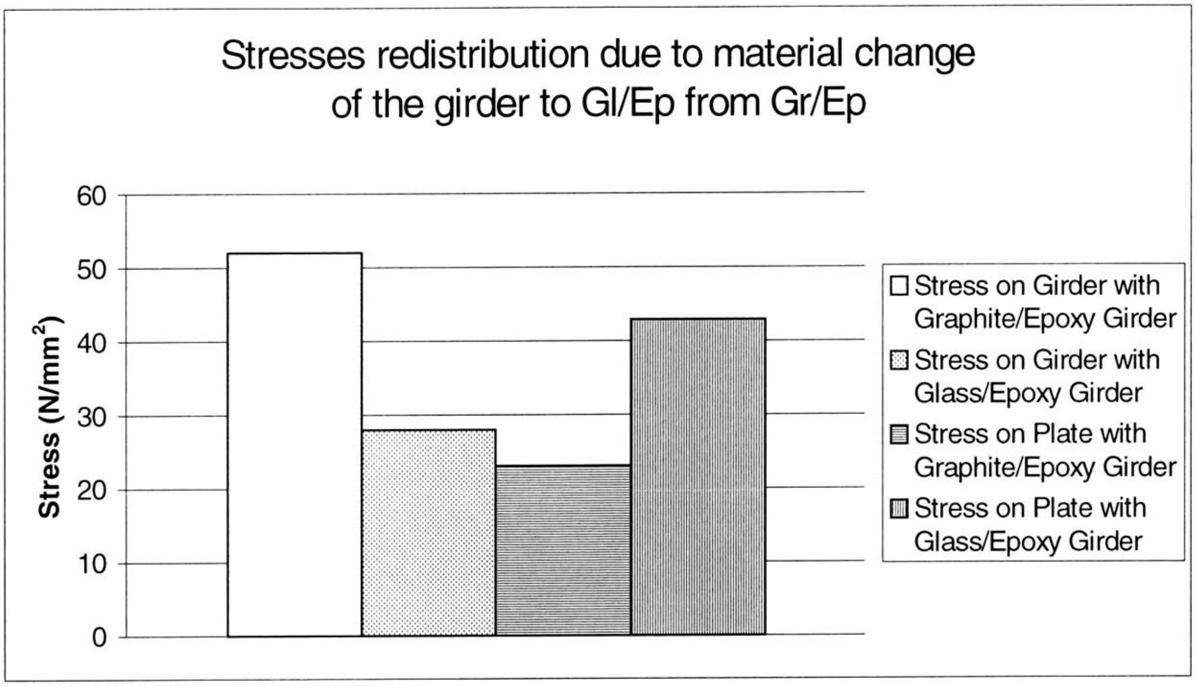

Figure 15: Stresses Redistribution on the plate and girder due to a change in material to Glass / Epoxy from Graphite Epoxy (Stresses on the Weather Deck)

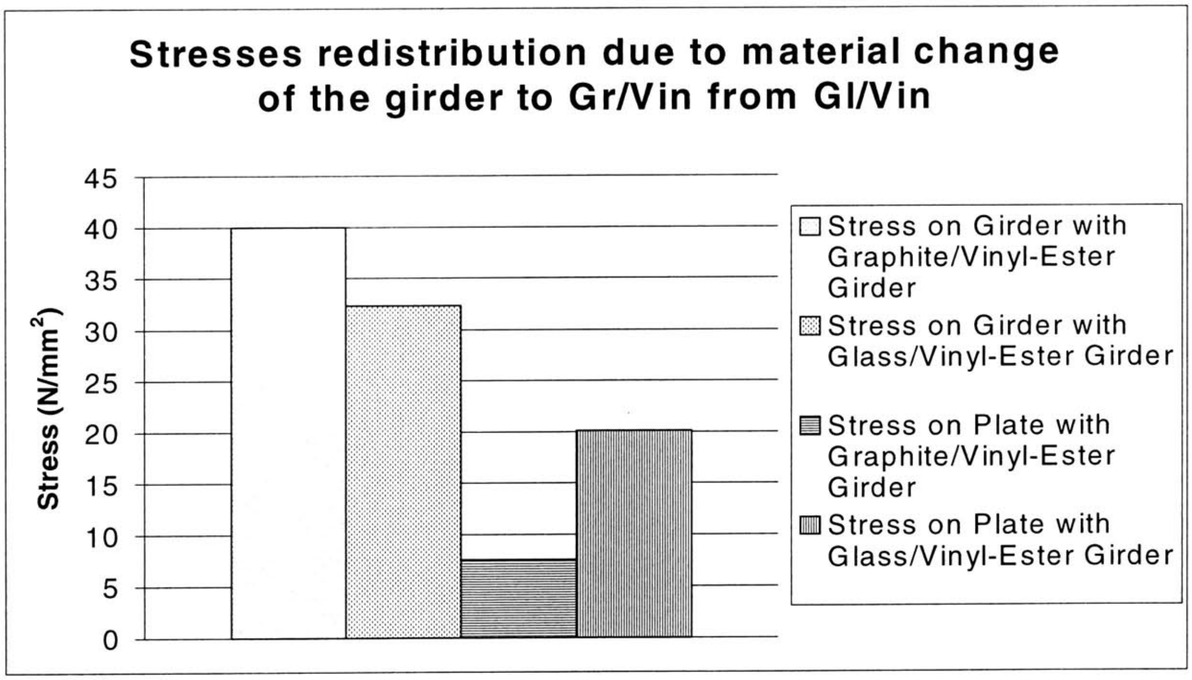

Figure 16: Stresses Redistribution on the plate and girder due to a change in material to Graphite / Vinyl Ester from Glass / Vinyl Ester (Stresses on the Weather Deck)

MAESTRO© has an objective to keep the weight to minimum during the structural analysis and structural optimization. Increasing the sizes of the scantlings with the stronger and lighter material while keeping the sizes of the less strong materials to the minimum acceptable for satisfying the local constraints, is an easy way for the program to increase the overall strength of the structure while keeping the weight to minimum. For this reasoning, in the experiments in which the material of the girders is a glass-based composite, the sizes of the plates and stiffeners are increased in such a way as to unload the stresses on the girders due to the longitudinal bending moments. That has as a result of a better main effect factor for the girder material as the glass-based composite compared to the graphite-based composite.

The experimental analysis also provides the relative importance percentage of each factor. As seen in Table 18, the most important factor for minimizing the total weight of the structure is the material of the plate, and this was indicated by the use of Graphite / Vinyl-Ester. The other three factors (the materials for the other three types of scantlings) do not affect the result significantly. For minimizing the cost, the factor that has the greatest effect is the material of the girder, and the analysis suggested using Glass / Vinyl Ester, which has the lowest cost among the materials.

So, despite the material selection for minimizing the total weight of the ship structure not being accurate, the final conclusions for the material selection for minimizing the weight of the ship structure by keeping at the same time the lower possible cost were acceptable. A verification run with MAESTRO© by using the results from the analysis, showed that the total weight and cost of the composite structure by using the suggested materials would be:

Weight:	66.36 tonnes
Cost:	$1.78 Mdol
Objective Function:	0.85

The resulting cost is lower than all the results from the individual experiments while the weight is among the lowest. The final sizes for the scantlings from this verification run can be found in Appendix 4.

A comparison between a module constructed by the use of the previous selected materials and the initial baseline module constructed by steel shows the followings:

1. The use of composite materials resulted in a decrease in the structural weight of 76%. This decrease in the structural weight is the expected, since Graphite-based composites are approximately 80% lighter than steel.

2. The resulting increase in cost is 36%. Despite the fact that the cost per unit weight of the composite materials is between 7.5 and 15 times higher than the steel, the decrease in the structural weight compensates for some of the increase in cost.

3. The objective function of the steel structure is equal to 1. On the other hand the objective function of the optimum design is 0.85. This decrease shows that the overall increase in cost and decrease in weight results in a better final design.

8 Alternative Designs

In the models that were examined until now, the basic design features of a steel ship were used. It is perhaps possible that other design concepts might be better for composite structures. One alternative design was considered. In this alternative, it was assumed that there was no difference between the sizes of the girders and the stiffeners, and they had a hat cross-section, as it can be seen in Figure 17.

Figure 17: Alternative cross-section of a deck

The reasons for these assumptions were the followings:

1. Because a large ship has much higher bending moments compared to a small ship, higher longitudinal stresses result on the different components of the ship's structure and especially on the girders and stiffeners are much higher. Depending the type of material, it was observed in the initial design concept that the size of the girders was near the maximum allowable limits, so, in order for the structure to be able to accommodate these longitudinal stresses, it was necessary to increase the size of the stiffeners as well as their number. Choosing the size of the girders and stiffeners as the same was an indirect way of increasing the number of girders while decreasing their size while on the other hand decreasing the number of stiffeners while increasing their size. The final goal was to decrease the total weight of the girders and stiffeners.

2. The hat cross section was used in order to increase the total moment of inertia of the cross section of the ship's structure, as well as make it easier to be fabricated

using composite materials [Ref. 29].

In order to model that concept on MAESTRO©, all the longitudinal scantlings were considered as girders, while the stiffeners were eliminated from the plates. The following Figure 18 shows the concept.

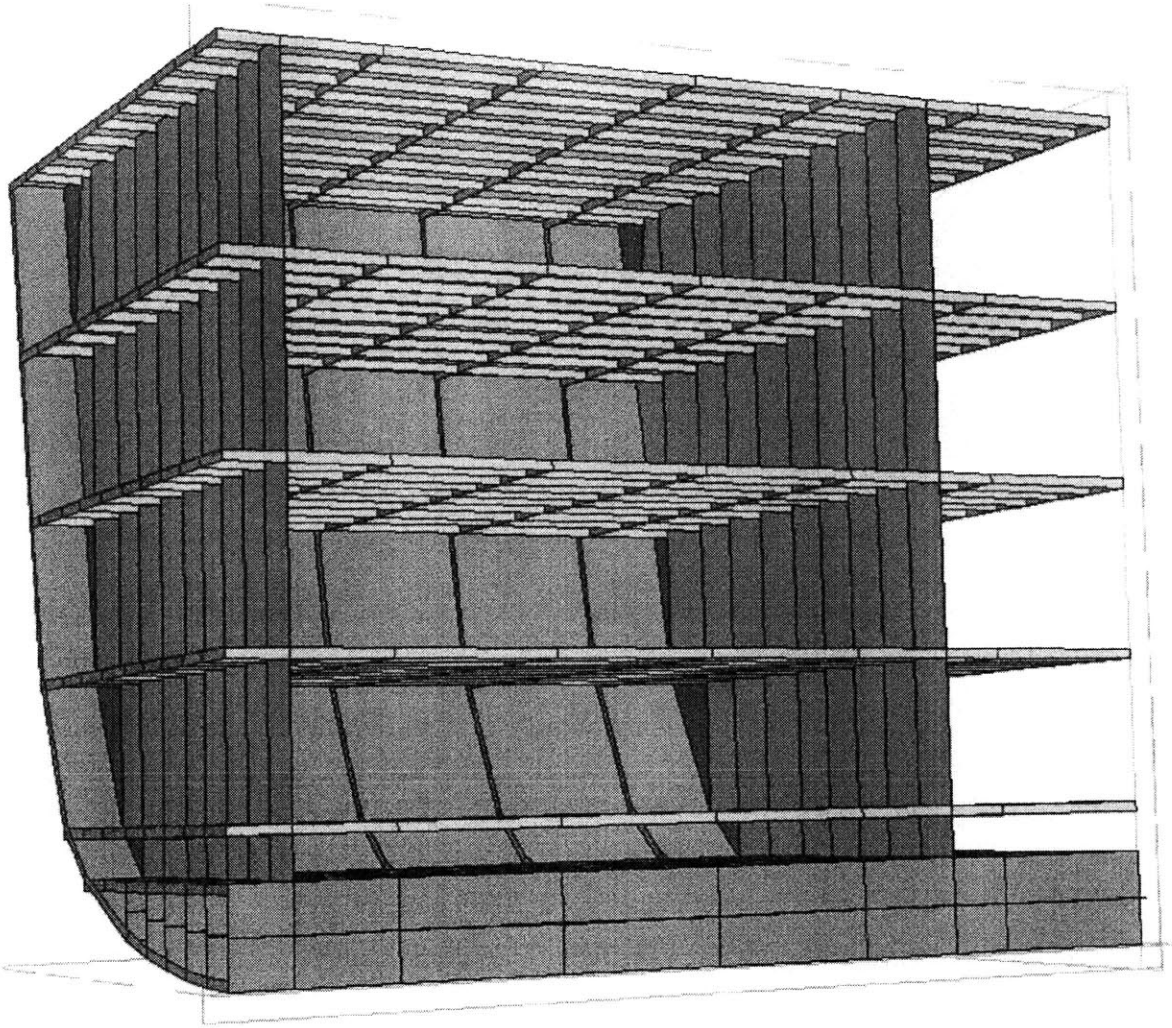

Figure 18: Alternative design with no stiffeners

For the analysis and structural optimization of this concept two different approaches were followed. The first was the minimization of the structural weight, while the second was the minimization of the manufacturing cost. For minimizing the structural weight, the sizes of each girder could be specified independently from the neighboring girders, while for minimizing the manufacturing cost, it was assumed that for each strake at each deck the sizes of the girders and frames were constant. With this assumption the number of the different type of scantlings was minimized and was limited to the number of decks. The material that was used was the Graphite / Epoxy composite. The analysis of these two alternatives showed that both of them were feasible, but the resulting structural weights were higher than the previous concept.

The first alternative resulted in a final structural weight of 120 tonnes, and the second one a structural weight of 110 tonnes, both of which were much higher than expected. In the initial design concept, the total structural weight of the module using Graphite / Epoxy was 65 tonnes, almost 40% to 45% less.

One possible reason for the higher weights is due to the fact that MAESTRO© considers the stiffeners as part of the plates during the structural analysis. In the analysis of this concept, since there were not any stiffeners, the thickness of the plates had to be increased in order for all the adequacy parameters to be positive. As has been shown in section 8, an increase in the size of the plates contributes to a significant increase in the total weight. To properly evaluate this concept, further analysis is necessary. The first step would be to conduct an analysis with a different design tool, e.g. a finite element program. This would eliminate the possibility that the modeling approach used in MAESTRO© artificially biased the result.

9 Conclusions and Recommendations for Future Work

During the last few decades many technological improvements have been taken place in the area of composite materials. Composites that a few decades ago were used only in the aerospace industry now have become available for common applications. In the years to come, even stronger, lighter and less expensive composite materials will be available, since there will be a significant increase in their demand.

This analysis showed the following conclusions:

a. The current commercially available composite materials have adequate strength for designing larger ships.

b. Despite the much higher cost of composite materials, due to weight savings the final cost is not respectively high.

c. A combination in use of both high end (graphite-based) and low end (glass-based) composite materials should be used for an affordable design

Beyond the potential for decreased structural weight of a ship, composite materials offer many other advantages, which balance the increase in the construction cost. Firstly, due to better corrosion characteristics in the marine environment, composites require less maintenance than steel or aluminum. Secondly, a decrease in the structural weight would allow a similar increase in the payload of a ship, which is very important for both military and commercial applications. Finally, for military applications, composites offer non-magnetic structures and less radar signature.

The change in designing large ships using composite materials rather than more conventional materials has many risks. More than one hundred years ago, the shipbuilding material changed from wood to steel. It is time now to change again, this time to composites. This analysis showed that an initial design of a composite ship by the same concept as a steel ship is both feasible and better. Moreover, it showed that stronger and lighter materials based on graphite fibers, despite the higher cost, are more desirable than more common composites. Finally, it showed that the material of the plates contributes significantly both to the reduction of the structural weight and the construction cost, so, the design of the plates would be the best area to concentrate on further research.

In addition to the design of the plates, many other areas should be also investigated:

- In this analysis, only single laminate composite plates were considered. A similar analysis should be undertaken considering sandwich designs for the strakes with and without the use of other structural elements.

- For the plates the laminates that were considered were orthotropic. A detailed analysis of the stress concentrations along a ship's hull could lead to the design of suitable anisotropic laminates which could further decrease the weight of the ship.

- During the analysis, the interlaminar stresses were not taken into consideration. It is necessary in a more detailed analysis to include these stresses, because they might have a significant affect on the structure, especially if sandwich and anisotropic laminates are used.

- MAESTRO© as presently developed is a program for doing a structural analysis of a ship. It was primarily developed for applications with more conventional design concept. There are limited capabilities for analyzing alternative design concepts as was demonstrated in this work. A modification in MAESTRO© code in order to be able to analyze alternative designs would be desirable. Moreover, a better and more robust optimization code is necessary to improve its usefulness in this type of broad evaluation.

- Other alternative design concepts should be also investigated.

- Other areas of interest, like processing and machining methods for composites, mechanical fastening and adhesive bonding, as well as environmental effects and fire tolerance should also be taken under consideration in a more detailed design

- Finally, a more accurate method of predicting the properties of composite materials would be desirable for any further analysis, or more experimental test should be undertaken in order to specify the exact properties of all the composite materials available in the marine industry.

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List of Appendices

Appendix 1

WEATHER DECK

SEGMENT GEOMETRY

SEG	YIB	ZIB	YOB	ZOB
1	0.00	41.84	11.24	41.84
2	11.24	41.84	24.73	41.84
3	24.73	41.84	33.24	41.84

SIDE SHELL

SEGMENT GEOMETRY

SEG	YUPR	ZUPR	YLWR	ZLWR
1	33.24	41.84	31.53	32.33
2	31.53	32.33	29.95	23.33
3	29.95	23.33	28.16	14.75
4	28.16	14.75	24.14	7.08

BOTTOM SHELL

SEGMENT GEOMETRY

SEG	YUPR	ZUPR	YLWR	ZLWR
1	24.14	7.08	14.05	1.82
2	14.05	1.82	11.24	1.13
3	11.24	1.13	8.43	0.62
4	8.43	0.62	5.62	0.30
5	5.62	0.30	2.81	0.08
6	2.81	0.08	0.00	0.00

INTERNAL DECKS

SEGMENT GEOMETRY

SEG	YIB	ZIB	YOB	ZOB
DECK NO. 1 CONTINUOUS				
SEG				
1	0.00	32.33	11.24	32.33
2	11.24	32.33	24.73	32.33
3	24.73	32.33	31.53	32.33
DECK NO. 2 PLATFORM				
SEG				
1	0.00	23.33	11.24	23.33
2	11.24	23.33	24.73	23.33
3	24.73	23.33	29.95	23.33
DECK NO. 3 PLATFORM				
SEG				
1	0.00	14.75	11.24	14.75
2	11.24	14.75	28.10	14.75
DECK NO. 4 INNER BOT				
SEG				
1	0.00	7.08	5.62	7.08
2	5.62	7.08	11.24	7.08
3	11.24	7.08	24.14	7.08
DECK NO. 5 INNER BOT				
SEG				
1	0.00	4.58	5.62	4.58
2	5.62	4.58	11.24	4.58

```
 3           11.24        4.58         20.95        4.58

                                        GIRDER PROPERTIES

GIRDER/STIFFENER   POSITION

                  YLOC         ZLOC

WET DECK

GIRDER

   1              0.00         41.84

   2              11.24        41.84

   3              24.73        41.84

INT DECK  1.

GIRDER

   1              0.00         32.34

   2              11.24        32.34

   3              24.73        32.34

INT DECK  2.

GIRDER

   1              0.00         23.33

   2              11.24        23.33

   3              24.73        23.33

INT DECK  3.

GIRDER

   1              0.00         14.75

   2              11.24        14.75

INT DECK  4.

GIRDER

   1              2.81         7.08

   2              5.62         7.08
```

3	8.43	7.08
4	11.24	7.08
5	14.05	7.08
INT DECK 5.		
GIRDER		
1	2.81	4.58
2	5.62	4.58
3	8.43	4.58
4	11.24	4.58
5	14.05	4.58
BOTTOM		
GIRDER		
1	0.00	0.00
2	2.81	0.08
3	5.62	0.30
4	8.43	0.62
5	11.24	1.13
6	14.05	1.82
BOTTOM		
STIFFENER		
1	0.00	2.29
2	2.81	2.33
3	5.62	2.44
4	8.43	2.60
5	11.24	2.85
6	14.05	3.20

SIDE AND BOTTOM FRAMES

FRAME SPACING, FT 8.00

SEGMENT GEOMETRY

SEG	YUPR	ZUPR	YLWR	ZLWR
SIDE FRAME				
SEG				
1	33.24	41.84	31.53	32.33
2	31.53	32.33	29.95	23.33
3	29.95	23.33	28.16	14.75
4	28.16	14.75	24.14	7.08
BOT FRAME				
SEG				
1	24.14	7.08	14.05	1.82
2	14.05	1.82	11.24	1.13
3	11.24	1.13	8.43	0.62
4	8.43	0.62	5.62	0.30
5	5.62	0.30	2.81	0.08
6	2.81	0.08	0.00	0.00

DECK BEAMS

SEGMENT GEOMETRY

SEG	YIB	ZIB	YOB	ZOB
WET DECK				
SEG				
1	0.00	41.84	11.24	41.84
2	11.24	41.84	24.73	41.84
3	24.73	41.84	33.24	41.84

```
DECK NO.  1

SEG

 1          0.00        32.33       11.24       32.33

 2          11.24       32.33       24.73       32.33

 3          24.73       32.33       31.53       32.33

DECK NO.  2

SEG

 1          0.00        23.33       11.24       23.33

 2          11.24       23.33       24.73       23.33

 3          24.73       23.33       29.95       23.33

DECK NO.  3

SEG

 1          0.00        14.75       11.24       14.75

 2          11.24       14.75       28.16       14.75

DECK NO.  4

SEG

 1          0.00        7.08        11.24       7.08

 2          11.24       7.08        24.14       7.08

DECK NO.  5

SEG

 1          0.00        4.58        11.24       4.58

 2          11.24       4.58        20.95       4.58
```

Appendix 2

```
%      This file calculates the equivalent engineering constants
%      for a unidirectional ply, by knowing the properties of the
%      constituents.

%      Input of the properties of the constituents

clear
ELm=3.38*10^9;              % Longitudinal modulus of matrix
ETm=3.38*10^9;              % Transverse modulus of matrix
poissonLTm=0.3;             % poisson ratio of matrix
GLTm=3.103*10^9;            % Shear modulus of matrix
Xtm=82.74*10^6;             % longitudinal tensile strength of matrix
Xcm=117.2*10^6;             % longitudinal compressive strength of matrix
Ytm=82.74*10^6;             % transverse tensile strength of matrix
Ycm=117.2*10^6;             % transverse compressive strength of matrix
Sm=12.41*10^6;              % shear strength of matrix
rom=1.12;                   % Specific gravity of matrix

ELf=85*10^9;                % Longitudinal modulus of fiber
ETf=85*10^9;                % Transverse modulus of fiber
poissonLTf=0.20;            % poisson ratio of fiber
GLTf=35.42*10^9;            % Shear modulus of fiber
Xtf=1550*10^6;              % longitudinal tensile strength of fiber
Xcf=1550*10^6;              % longitudinal compressive strength of fiber
Ytf=1550*10^6;              % transverse tensile strength of fiber
Ycf=1550*10^6;              % transverse compressive strength of fiber
Sf=35*10^6;                 % shear strength of fiber
rof=2.5;                    % Specific gravity of fiber
```

```
Vf=0.70;                        % Volume fraction of the fiber

%       Specific gravity of the composite

Vm=1-Vf;
ro=rof*Vf+rom*Vm

%       Longitudinal Young's modulus

EL=ELf*Vf+ELm*Vm

%       Transverse Young's modulus

ET=inv(Vf/ETf+Vm/ETm)

%       Major Poisson ratio

poissonLT=poissonLTf*Vf+poissonLTm*Vm

%       In Plane Shear modulus

ksi=1+40*Vf^10;
ni=((GLTf/GLTm)-1)/((GLTf/GLTm)+ksi);
GLT=inv(Vf/GLTf+Vm/GLTm)
GLT=GLTm*(1+ksi*ni*Vf)/(1-ni*Vf)

%       Longitusinal tensile strength

epsilonLf=Xtf/ELf;
epsilonLm=Xtm/ELm;
Xt=Xtf*Vf+epsilonLf*ELm*(1-Vf)
```

```
%       Longitudinal compressive strength

flag1=sqrt(4*Vf/pi);
epsilonT1=epsilonLm*(1-Vf^(1/3));
epsilonT2=epsilonLm*(flag1*(ELm/ELf-1)+1);
epsilonT=min([epsilonT1 epsilonT2])
% Due to shear/extension fiber microbuckling failure mode
Sigma1=(Vf+(1-Vf)*ELm/ELf)*sqrt(Vf*ELm*ELf/(3*(1-Vf)));
Sigma2=GLTm/(1-Vf);
Xc1=min([Sigma1 Sigma2]);
% Due to shea stress failure of fibers mode
S12=Sf*Vf+Sm*Vm;
Xc2=2*S12;
% Final strenght
Xc=min([Xc1 Xc2])

%       Transverse tensile strength

Yt=ET*epsilonT

%       Transverse compressive strength

epsilonCm=Ycm/ETm;
epsilonC=(flag1*ETm/ETf+(1-flag1))*epsilonCm;
Yc=ET*epsilonC

%       In-Plane shear strength

gammam=Sm/GLTm
S=GLT*(flag1*GLTm/GLTf+(1-flag1))*gammam
```

Appendix 3

```
%       This file calculates the equivalent engineering constants
%       for a laminate.

clear
angle=[0;45;-45;90;90;-45;45;0];        % direction of each ply
plynumb=length(angle);                  % number of plies
EL=38.6*10^9;                           % Longitudinal modulus
ET=8.23*10^9;                           % Transverse modulus
poissonLT=0.26;                         % poisson ratio
GLT=8.86*10^9;                          % Shear modulus
Xt=1062*10^6;                           % longitudinal tensile strength
Xc=-496*10^6;                           % longitudinal compressive strength
Yt=35.56*10^6;                          % transverse tensile strength
Yc=-135.32*10^6;                        % transverse compressive strength
S=60.78*10^6;                           % shear strength

%       Construction of properties matrix

properties=[EL ET poissonLT GLT];

%       Construction of thickness matrix

thick=1/plynumb;
for i=1:plynumb
  tk(i)=thick;
end

%       calculations of Amatrix, Q and Qbar for each ply
```

```
[A,Q,Qtotal]=Amatrix(properties,angle,tk);
alpha=inv(A);
%       Calculations of equivalent engineering constants
%       for the laminates

E=1/alpha(1,1)
plate_poisson=-alpha(1,2)/alpha(1,1)

%       Longitudinal Tensile Strength

for i=1:plynumb/2
fail=0;
dR=100000000;
while dR>=1
  fail=fail+dR;
  N=[fail;0;0];
  flag=Tsigma(angle(i))*N;
  if flag(1)>=0
    f1=1-flag(1)/Xt;
  else
    f1=1-flag(1)/Xc;
  end
  if flag(2)>=0
    f2=1-flag(2)/Yt;
  else
    f2=1-flag(2)/Yc;
  end
  if flag(3)>=0
    f3=1-flag(3)/S;
  else
    f3=1-flag(3)/(-S);
  end
```

```
  if (f1<0|f2<0|f3<0)
    fail=fail-dR;
    dR=dR/10;
  end
end
Long_tensile(i)=fail;
end

%       Longitudinal Compressive Strength

for i=1:plynumb/2
fail=0;
dR=100000000;
while dR>=1
  fail=fail+dR;
  N=[-fail;0;0];
  flag=Tsigma(angle(i))*N;
  if flag(1)>=0
    f1=1-flag(1)/Xt;
  else
    f1=1-flag(1)/Xc;
  end
  if flag(2)>=0
    f2=1-flag(2)/Yt;
  else
    f2=1-flag(2)/Yc;
  end
  if flag(3)>=0
    f3=1-flag(3)/S;
  else
    f3=1-flag(3)/(-S);
  end
```

```
  if (f1<0|f2<0|f3<0)
    fail=fail-dR;
    dR=dR/10;
  end
end
Long_comp(i)=fail;
end


%       Transverse Tensile Strength

for i=1:plynumb/2
fail=0;
dR=100000000;
while dR>=1
  fail=fail+dR;
  N=[0;fail;0];
  flag=Tsigma(angle(i))*N;
  if flag(1)>=0
    f1=1-flag(1)/Xt;
  else
    f1=1-flag(1)/Xc;
  end
  if flag(2)>=0
    f2=1-flag(2)/Yt;
  else
    f2=1-flag(2)/Yc;
  end
  if flag(3)>=0
    f3=1-flag(3)/S;
  else
    f3=1-flag(3)/(-S);
```

```
  end
  if (f1<0|f2<0|f3<0)
    fail=fail-dR;
    dR=dR/10;
  end
end
Tran_tensile(i)=fail;
end

%       Transverse Compressive Strength

for i=1:plynumb/2
fail=0;
dR=100000000;
while dR>=1
  fail=fail+dR;
  N=[0;-fail;0];
  flag=Tsigma(angle(i))*N;
  if flag(1)>=0
    f1=1-flag(1)/Xt;
  else
    f1=1-flag(1)/Xc;
  end
  if flag(2)>=0
    f2=1-flag(2)/Yt;
  else
    f2=1-flag(2)/Yc;
  end
  if flag(3)>=0
    f3=1-flag(3)/S;
  else
    f3=1-flag(3)/(-S);
```

```
  end
  if (f1<0|f2<0|f3<0)
    fail=fail-dR;
    dR=dR/10;
  end
end
Tran_comp(i)=fail;
end

%       Shear Strength

for i=1:plynumb/2
fail=0;
dR=100000000;
while dR>=10000
  fail=fail+dR;
  N=[0;0;fail];
  flag=Tsigma(angle(i))*N;
  if flag(1)>=0
    f1=1-flag(1)/Xt;
  else
    f1=1-flag(1)/Xc;
  end
  if flag(2)>=0
    f2=1-flag(2)/Yt;
  else
    f2=1-flag(2)/Yc;
  end
  if flag(3)>=0
    f3=1-flag(3)/S;
  else
    f3=1-flag(3)/(-S);
```

```
  end
  if (f1<0|f2<0|f3<0)
    fail=fail-dR;
    dR=dR/10;
  end
end
Shear_strength(i)=fail;
end

tensile=[mean(Long_tensile) mean(Long_comp)];
long_strength=min(tensile)
shear_strength=mean(Shear_strength)
```

Function Amatrix.m

```
% The following program calculates the A matrix of a laminate as inputs are a
% matrix with the properties of the materials a matrix with the directions of the
% fibers for each ply, and a matrix with the thickness of each ply.

function [A,Q,Qtotal]=Amatrix(properties,angle,tk);

% Separation of properties and other parameters
EL=properties(1);          % Longitudinal modulus
ET=properties(2);          % Transverse modulus
poissonLT=properties(3);     % Poisson Ratio
GLT=properties(4);          % Shear Modulus
plynumb=length(angle);      % Number of Plies

% Construction of Q matrix for the unidirectional ply
Q=Qmatrix(EL,ET,poissonLT,GLT);

% Calculation of Qbars for each ply
```

```
for i=1:plynumb
  Qb=Qbar(Q,angle(i));
  Qtotal(1,i)=Qb(1,1);
  Qtotal(2,i)=Qb(1,2);
  Qtotal(3,i)=Qb(1,3);
  Qtotal(4,i)=Qb(2,1);
  Qtotal(5,i)=Qb(2,2);
  Qtotal(6,i)=Qb(2,3);
  Qtotal(7,i)=Qb(3,1);
  Qtotal(8,i)=Qb(3,2);
  Qtotal(9,i)=Qb(3,3);
end


% Construction of A matrix
 Atotal=Qtotal*tk';
for i=1:3
  for j=1:3
    A(i,j)=Atotal((i-1)*3+j);
  end
end
```

Function Qmatrix.m

```
%       The following function calculates the Q matrix of an orthotropic 2D ply in
%       plane stress from given EL, ET, poissonLT, GLT where:
%       EL is the young modulus in the longitudinal direction
%       ET is the young modulus in the transverse direction
%       poissonLT is the poisson ratio corresponding at the LT
%       GLT is the shear nodulus corresponding at the LT
%       poisson TL is the poisson ratio corresponding at the TL

function Q=Qmatrix(EL,ET,poissonLT,GLT)
```

```
poissonTL=ET*poissonLT/EL
Q(1,1)=EL/(1-poissonLT*poissonTL);
Q(1,2)=(poissonLT*ET)/(1-poissonLT*poissonTL);
Q(2,1)=Q(1,2);
Q(1,3)=0;
Q(2,2)=ET/(1-poissonLT*poissonTL);
Q(2,3)=0;
Q(3,1)=0;
Q(3,2)=0;
Q(3,3)=GLT;
```

Function Qbar.m

```
% the following function rotates a matrix by an angle theta
function Qb=Qbar(Q,theta)
Qb=inv(Tsigma(theta))*Q*Tepsilon(theta);
```

Function Tsigma.m

```
% the following function calculates the rotation matrix Tsigma
function Tsigma=Tsigma(theta)
c=cos(theta*pi/180);
s=sin(theta*pi/180);
Tsigma=[c^2 s^2 2*c*s;s^2 c^2 -2*c*s;-c*s c*s (c^2-s^2)]
```

Function Tepsilon.m

```
% the following function calculates the rotation matrix Tepsilon
function Tepsilon=Tepsilon(theta)
c=cos(theta*pi/180);
s=sin(theta*pi/180);
Tepsilon=[c^2 s^2 c*s;s^2 c^2 -c*s;-2*c*s 2*s*c (c^2-s^2)];
```

Appendix 4

Cost= 57.40
Density= 1.60E-06

Plates

TPL	BREADTH	Weight
22	860.23	443.30
22	852.28	439.20
22	865.79	446.17
18	863.13	363.92
18	885.27	373.26
19	2265.50	1008.27
7	1240.16	203.35
18	1400.00	590.28
18	1380.00	581.85
18	1310.00	552.34
18	1210.00	510.17
18	1060.00	446.93
18	850.00	358.39
13	2100.00	639.48
8	860.00	161.16
7	850.00	139.37
5	860.00	100.72
8	850.00	159.28
8	860.00	161.16
15	980.00	344.33
15	2100.00	737.86
12	860.00	241.74
13	850.00	258.84
9	860.00	181.30
12	850.00	238.92
25	860.00	503.62
7	2634.73	432.01
10	1050.00	245.95
9	4120.00	868.56
8	3420.00	640.88
5	2675.07	313.30
7	1590.00	260.71
7	4120.00	675.55
9	3420.00	720.99
7	2781.73	456.11
10	2070.00	484.88
9	4120.00	868.56
7.5	3420.00	600.83
5	2963.41	347.07
32	2590.00	1941.38
30	4120.00	2895.21
30	3420.00	2403.30
	Total =	24340.51
	Value=	1397023.67

Cost= 31.19
Density= 1.62E-06

Frames

	HSW	TSW	BSF	TSF	Area	Length	Weight
1	350	10	250	25	9750.00	860.23	13.59
2	200	7	100	8	2200.00	852.28	3.04
3	120	5	60	6	960.00	865.79	1.35
4	120	5	60	6	960.00	863.13	1.34
5	120	5	60	6	960.00	885.27	1.38
6	262.4	5	150	12	3112.00	2265.50	11.42
7	259.3	5	150	12	3096.50	1240.16	6.22
8	0	0	0	0	0.00	1400.00	0.00
9	0	0	0	0	0.00	1380.00	0.00
10	0	0	0	0	0.00	1310.00	0.00
11	0	0	0	0	0.00	1210.00	0.00
12	0	0	0	0	0.00	1060.00	0.00
13	0	0	0	0	0.00	850.00	0.00
14	91.57	5	36.63	5.001	641.04	2100.00	2.18
15	0	0	0	0	0.00	860.00	0.00
16	0	0	0	0	0.00	850.00	0.00
17	0	0	0	0	0.00	860.00	0.00
18	0	0	0	0	0.00	850.00	0.00
19	0	0	0	0	0.00	860.00	0.00
20	150	7	100	7	1750.00	980.00	2.78
21	89.02	5	35.62	5.001	623.24	2100.00	2.12
22	0	0	0	0	0.00	860.00	0.00
23	110.1	5	54.96	5	825.30	850.00	1.14
24	99.05	5	39.69	5.001	693.74	860.00	0.97
25	81.16	5	34.63	5	578.95	850.00	0.80
26	94.34	5	38.19	5	662.65	860.00	0.92
27	258.7	5.016	105.9	5.189	1847.15	2634.73	7.88
28	150	5	100	8	1550.00	1050.00	2.64
29	120	3.66	70.7	7.06	938.34	4120.00	6.26
30	120	3.66	70.7	7.06	938.34	3420.00	5.20
31	100	4	50	5	650.00	2675.07	2.82
32	130	5	80	9	1370.00	1590.00	3.53
33	120	5	70	7	1090.00	4120.00	7.28
34	120	5	70	7	1090.00	3420.00	6.04
35	0	0	0	0	0.00	2781.73	0.00
36	150	6	90	9	1710.00	2070.00	5.73
37	160	6	100	10	1960.00	4120.00	13.08
38	150	6	90	9	1710.00	3420.00	9.47
39	0	0	0	0	0.00	2963.41	0.00
40	160	7	120	12	2560.00	2590.00	10.74
41	150	6	100	10	1900.00	4120.00	12.68
42	150	6	100	10	1900.00	3420.00	10.53
						Total =	1071.82
						Value=	33432.26

length= 14640.00

Cost= 61.99

Density= 1.60E-06

Stiffeners

	# of stiff.	**HSW**	**TSW**	**BSF**	**TSF**	**Area**	**Weight**
1	2	197	3.31	60.5	6.52	1046.53	49.03
2	2	166	3.03	66.4	10.5	1200.18	56.23
3	2	163	3.01	65.2	10.8	1194.79	55.97
4	2	161	3.01	63.5	10.3	1138.66	53.34
5	2	158	3.02	63.4	10.5	1142.86	53.54
6	2	202	3.04	83.4	13.7	1756.66	82.30
7	6	113	3	28.2	3	423.60	59.53
8	4	205	1.79	29.3	5.67	533.08	49.95
9	2	226	3.39	57.9	6.64	1150.60	53.90
10	2	218	3.27	56.1	6.15	1057.88	49.56
11	2	212	3.19	54.3	5.88	995.56	46.64
12	2	201	3.01	50.2	6.13	912.74	42.76
13	2	198	3	49.6	3.52	768.59	36.01
14	2	149	3	59.7	9.85	1035.05	48.49
15	2	183	3	45.9	3.03	688.08	32.24
16	2	179	3	44.7	3	671.10	31.44
17	3	178	3	44.5	3.05	669.73	47.06
18	2	141	3	35.2	3	528.60	24.76
19	2	131	3	32.6	3.1	494.06	23.15
20	1	143	3	57.1	9.42	966.88	22.65
21	2	184	3.03	71.8	11.8	1404.76	65.81
22	2	137	3.08	54.7	9.02	915.35	42.88
23	2	135	3.02	54.2	8.94	892.25	41.80
24	2	128	3.05	51.5	8.5	828.15	38.80
25	2	119	3.09	47.5	7.83	739.64	34.65
26	2	184	3.07	70.6	11.6	1383.84	64.83
27	11	114	3	42.8	3	470.40	121.21
28	1	97.7	3	39.1	6.45	545.30	12.77
29	6	133	3.06	52.9	8.74	869.33	122.18
30	7	125	3.06	42.2	6.96	676.21	110.88
31	11	70.7	3	31.4	5.19	375.07	96.64
32	3	121	3.81	48.3	7.97	845.96	59.45
33	10	126	3.08	46.7	4.28	587.96	137.72
34	6	122	3.04	42.6	7.03	670.36	94.21
35	8	200	3	59.1	3.03	779.07	145.99
36	3	131	3.01	52.3	8.63	845.66	59.43
37	8	146	3.07	56.7	5.87	781.05	146.36
38	7	153	3.03	55.4	3.06	633.11	103.81
39	7	181	3	45.3	3	678.90	111.32
40	5	150	5	75	10	1500.00	175.68
41	7	150	5	75	7.5	1312.50	215.21
42.00	7	150	5	75	7.5	1312.50	215.21
						Total =	3135.38
						Value=	194352.79

Cost= 33.69
Density= 2.08E-06

Girders

HSW	TSW	BSF	TSF	Area	Weight
400	12	200	10	6800.00	207.07
300	7.5	150	10	3750.00	114.19
300	7.5	150	5	3000.00	91.35
250	7	150	10	3250.00	98.97
250	7	150	10	3250.00	98.97
700	18	150	8	13800.00	420.23
650	15	300	9	12450.00	379.12
500	14	140	8	8120.00	247.26
300	7.5	200	15	5250.00	159.87
700	18	300	9	15300.00	465.90
400	10	90	13	5170.00	157.43
450	12	200	11	7600.00	231.43
700	18	350	7	15050.00	458.29
400	10	150	7	5050.00	153.78
300	16	200	10	6800.00	207.07
900	30	300	35	37500.00	1141.92
350	15	150	10	6750.00	205.55
				Total =	4632.85
				Value=	156066.67

Total Weight= 66361.12
Total Value= 1780875.40