COMPARATIVE ANALYSIS OF MATERIALS IN RECREATIONAL BOAT DESIGN: FIBER REINFORCED PLASTIC BOAT IN SERIAL PRODUCTION

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ABSTRACT

This study aims to reveal the suitable boat construction material for serial production and the innovative design opportunities for the competition in the boat market in which the manufacturers and designers have to differentiate themselves by innovative designs, attractive products and new production techniques.

Although the building material, from which the vessel is to be built, has the most important affect on design and production, the material choice and construction methods are first determined in design stage. Thus as the second chapter after introduction, the design stage is presented, which affect product sale more than the others. This chapter is formed by introducing the vessel characteristic, design requirements, design process and design methods, which form the boat. In addition, the computer's role, which brings a lot of easiness, cost and time advantage to area of boat design, is mentioned.

The materials used for boat construction are important for design process. So during the third chapter the materials such as steel, ferrocement, aluminium, wood and composite materials are discussed. By the help of this discussion, a designer can get an idea for the suitable material for his\ her design and by the help of the comparison graphics of materials he\ she can get a quick idea about the differences of the materials.

Materials used in boat construction have taken up within the framework of a comparison consisting of material's mechanical characteristics, resistance to different affects, design opportunities and cost. As the result of material comparison, FRP (fiber reinforced plastic) recreational boat construction methods, which are conventional method such as hand lamination and spray lamination and more industrialized techniques such as vacuum bag and SMC etc., are presented in chapter four. In addition, future trends of FRP boat building and computer application (CNC milling), which give the advantages such as time labor and cost save, are presented in chapter four.

Finally with this research someone as a designer or manufacturer can create more effective products, which cover the consumer demand, in considering design process, material characteristic and production techniques mentioned in the thesis.

Keywords: Recreational boat design, boat construction materials, FRP boat production methods.

ÖZET

Bu çalışma; tasarımcı ve üretici için, tekne yapımına özellikleriyle tasarım yeniliği getirebilecek, müşteri talebini karşılamada hızlı ve kaliteli üretim yöntemleriyle üstünlük saglayacak, seri üretime uygun malzemenin ortaya çıkarılmasını amaçlamaktadır.

Tekne yapımında kullanılan malzeme, her nekadar tasarımı ve üretim yöntemlerini etkilese de, malzeme seçiminin ve üretim yönteminin karar verildiği bölüm tasarım sürecidir. Bu nedenle taktim bölümünden sonra ikinci bölüm olarak; tekneyi biçimlendiren tekne tasarım karakteristikleri, müşteri talebi, tasarım kısıtlamaları, tasarım süreci ve yöntemleri gibi konuları kapsayan tasarım bölümünü ele alınmıştır. Bunlara ek olarak bilgisayar teknolojisinin tasarıma olan getirilerine değinilmiştir.

Üçüncü bölümde ise tekne tasarımının en önemli etkenlerinden biri olan malzemeler; malzeme özellikleri, maliyet, malzemenin darbe, ısı gibi dış etkilere dayanımı ve verdikleri tasarım imkanları gibi özellikleri gözönüne alınarak tablolar ve tecrübelerden elde edilen bilgilerle karşılaştırmalar şeklinde sunulmuştur.

Karşılaştırma sonucunda FRP(Elyafla Güçlendirilmiş Plastik)’nin seri üretim için uygun malzeme olarak belirlenmesiyle; dördüncü bölümde bu malzemeye ait üretim yöntemleri ve bu yöntemler içinde kullanılan ekipmanlar avantaj ve dezavantajlarıyla anlatılmıştır. Buna ek olarak FRP ve üretim yöntemleri ile ilgili yenilikler ve bilgisayar teklolojinin üretim alanındaki yerine değinilmiştir.

Özet olarak, tez boyunca bahsedilen tasarım evresi, tekne yapımında kullanılan malzemeler ve FRP nin seri üretim yöntemleriyle; tasarımcı yada üreticinin bunları gözönüne alarak, müşteri talebini karşılayan, cezbedici, seri üretime uygun ürünler ortaya çıkarabileceği düşünülmüştür.

Anahtar Kelimeler: Tekne tasarımı, tekne yapım malzemeleri, FRP tekne üretim yöntemleri.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Definition Of The Problem

Recreational boats (crafts), which is used for leisure, sport and pleasure activity, are the water crafts both sailboat and motorboat. Boat design is getting more important (like the other craft design areas such as car and plane design) in Turkey and also all around the world. Unlike commercial ships, aesthetic is very important in small boat design. It also plays an important role to sell the vessel. In fact the exterior design, construction, interior design and the material used for the boat design are considered as a whole, which cause designers, craftsmen and engineers to work together. This is a multidisciplinary design problem dealing with different aspects such as structure, form, stability, mission requirements and hydrodynamics etc.

There are a lot of factors, which affects the boat design such as aim, size, material, cost and weight of a boat. The material choice is one of the most important factors for the boat design as same as other design objects. As a plus to this, the increasing market demand for the recreational boats has caused the materials and production methods to get important. Because the material and the production method has to be suitable for serial production that cover the increasing market demand.

There are different materials used in recreational boat building industry such as steel, ferrocement, aluminum, wood and composites. They all have different material properties and manufacture processes. But nowadays for recreational boats, the most used material is FRP (Fiber Reinforced Plastic). Because of this reason, in this thesis; reader can find a conclusion that shows why the composites are most used and more suitable material than the other materials for recreational boat industry by the help of the comparisons of material’s mechanical characteristics and the material resistance properties to different affects. As a conclusion, FRP has a preference when compared with other materials by heat resistance, easy repair, low maintenance, competitive cost, lightweight, time gain in limited production, less labor and by being suitable for serial production. Besides these extensive properties, FRP also allow to be manufactured complex formed designs. All boat forms can be manufactured by FRP if the mould is prepared. So this gives a unique opportunity to designer to free himself for his designs. Thus the product’s design becomes attractive and this affects the sale of the product.

In this thesis also the affect of the computer on manufacture and design process is mentioned. By the help of the computer, a designer can easily get estimated cost, boat dimensions, hydrostatic analysis. Also the time needed for drawings gets shorter and the spiral circle, which is necessary for the design process gets faster. In addition these profits, 3D drawings, which have complex forms made by the computer, are used for the CNC (Computer Numerical Control) production to produce the mold which have more clean and right finish according to conventional boat molding.

As a brief, boat design is a whole including manufacturing method, the material choice and design process. A change in any of these components affects the each other’s. This thesis presents that FRP is the most suitable material for serial production of recreational boats when compared with other materials used in boat building. With this conclusion, as the last chapter; the manufacture method of FRP, future trends for FRP production technologies and materials are presented.

1.2. Aim Of The Study

Boat design is a process, which includes material choice manufacture process choice and the design. Material choice is one of the most important factors, which affects design and manufacture process and this choice is made during design process. Because of this reason after introduction, boat design chapter is presented. The aim is to emphasize the place of material choice and manufacture process choice made during design period and also to give the brief knowledge to evaluate the period of material choice and manufacture process.

There are a lot of factors, which affects boat design. These are the aim, the dimensions, materials, construction techniques and related to these, the weight, production cost, maintenance cost, seakeeping, impact resistance and corrosion. Boat design is a process, which has some assumptions and these assumptions changes by different ways of experiments till to the final result. This period is called as design circle and for most of the vessel this circle is used.

There are a lot of boat construction materials such as wood, steel, aluminum, ferrocement and composites. The very first boat in the history is a wooden boat so the lot of theoretical and practical knowledge is learned from these wooden boats. After the industrial revolution, usage of steel in boat construction is increased which allowed the designers to design bigger boats. Steel is still common for commercial and military boats. Afterwards aluminum and ferrocement has been used for boats. Lots of boats are produced with these materials also. Composites first used in space and aviation areas. Then, composites were used as a new material for military aimed boats and small boats. The material chapter's (chapter 3) aim is to explain the properties of the materials and to try to find out the most suitable material for serial production of small boats by comparing the different materials.

By deciding the composites as the most suitable material for serial production of small boats, the manufacture process with this material is explained in the fourth chapter. The aim here is to show a way to find the manufacture method by explaining the advantages and disadvantages of the serial production.

1.3. The Method Of The Study

This thesis consists of three chapters except introduction and conclusion, which completes each other. In the first chapter the boat design process, design characteristics, design methods are mentioned and some comparisons are made to find out an optimum design by giving examples of boat designs. This comparison is made by two alternatives for the same boat by taking care of different speed, comfort, dimension, form, care expenses and cost estimates. By the help of this; a designer can decide what is important to find out an optimum design during design process, sometimes by comparisons and sometimes by explanations. This introduces the affects and the importance of the databases, materials and the manufacture processes of the second and third chapters to the reader and forms a ground for the material part formed in chapter two.

In chapter two the materials used in boat production is being explained and comparisons between materials are made. This comparison is made to find out the most suitable material for serial production by taking care of the material's mechanical characteristics, outer affects to material (such as impact, corrosion), cost estimates, labor and time etc. Different tables and practical experience support the comparisons. After finding the most suitable material as FRP, the manufacture methods of FRP boats are explained as third chapter.

At the third chapter the conventional and industrialized construction techniques of FRP are explained by comparison of cost estimates, labor, time, easiness for construction processes, etc. As a plus to this; the equipments, which are used in conventional and the industrialized construction, are introduced with their advantages and disadvantages. At the end of the chapter, the future trends of FRP are presented which consist of development in construction techniques, material and equipment. In addition, production methods of gulet, which is a traditional yacht built generally in Bodrum, are mentioned.

CHAPTER 2

RECREATIONAL BOAT DESIGN

The marine industry is a competitive market where manufacturers and designers must differentiate themselves for the competition by innovative designs, attractive products, and new production techniques.

Recreational boats have been growing in popularity especially with the new production techniques and new materials, which gives unusual design opportunity.

Boat design is an iterative, 'trial and error' procedure where the final result has to satisfy certain requirements that specified beginning of the design. For a new design, designer has to start with a number assumption and work through the design with them until all assumptions satisfy the requirements. Of course it wont be in certain case for the first iteration, so the designer will have to change some assumptions and repeat the process, normally several times. This turn called as design spiral.

This chapter is concerned with the boat design characteristics and design process including how to begin a design, how assumptions are reached to final product and how operates the design spiral. Beside design process and design methods, the computer application in design will be mentioned.

2.1. Recreational Boats

Recreational boats (crafts), which used for leisure, sport and pleasure activity, are the water crafts in different sizes and forms. These boats are called in different names such as pleasure craft (boat) and leisure craft in literature because of its characteristics, which define it.

Recreational crafts can be classified in small crafts. "There is several different definition of a small craft in the open literature. As it comes with its name, all of the definitions are related with the size, especially the length. For example,

- Less than 150 ft in length
- Less than approximately 100 ft or 30 m in length.
- A pleasure craft with a length between 2.5 and 24m.
- Below the size covered by Merchant Shipping classification

- A craft in which all hull and internal systems can be designed and specified by one person.

A classification of small craft devised by Southampton Institute contains some 90 different types small craft covering a wide range of functional roles.” (Roy 1991, Aksu and Tuzcu 1995) This small craft classification consists of three subdivision as naval, commercial and pleasure crafts. (see table 2.1. and table 2.2.)

Recreational crafts are defined in Directive 94/25/EC of the European Parliament and the Council as "any craft intended for sport or leisure purposes, regardless of the type or the means of propulsion, with a hull length of 2.5 to 24 meters, measured according to the appropriate harmonized standards'. WEB_8 (2004)

Recreational boats have been growing in popularity throughout the world. This growth has created the market for new boats built with improved hull materials and new hull forms, propulsion motors and fabrication techniques. A visitor in a boat show can see sailboats, motor boats, outboard engines and accessories being sold through a well developed factory and dealership network. This approach differs significantly from the traditional custom ship design and shipyard production of single and multiple vessels.

This situation makes the development of boat design a complex problem. The technical requirements of boat size, weight, power and speed are intermixed with the consumer’s needs for quality of the boat finish and accessories as well as its price. As a consequence there are a number of important parameters, which must be properly selected. The boat designer needs access to current and projected boat trends and consumer needs.

The other consumer requirement is that the recreational boats should be low maintenance and long life. This has resulted in the majority of recreational boats being built in fiberglass/composite materials.

“Over 30 years of FRP boat-building experience stands behind today's pleasure boats. Complex configurations and the advantages of seamless hulls were the driving factors in the development of FRP boats. FRP materials have gained unilateral acceptance in pleasure craft industry because of light weight, vibration damping, corrosion resistance, impact resistance, low construction costs and ease of fabrication, maintenance and repair.

Fiberglass construction has been the mainstay of the recreational boat building industry since the mid 1960s. After about 20 years of development work, manufacturers 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 startup builders. Naval and racing vessels as in all transportation craft area drive current leading edge marine composite manufacturing technologies". (Greene 2004)

The technologies coming with the developments of naval and racing vessels have affected the design and production techniques as computer and material industry developments affected. Thus the process and the techniques used in marine industry have changed and become faster, more quality, safety and reliable. In addition the developments in production, different designs, which have complex forms, are now applicable.

Figure 2.1. Antrim 40' Racer / Cruiser Trimaran-hull: Composite sandwich construction with Kevlar and carbon fiber reinforcements. WEB_1 (2004)

- **SMALL CRAFTS**
  - **NAVAL**
    - **OFFENSIVE**
      - **.GUNBOATS**
      - **.M.T.B.'S**
      - **.MISSILE CARRIERS**
      - **.SUBMARINES**
      - **.LANDING CRAFT**
      - **.INFLATABLS**
      - **.AMPHIBIOUS**
    - **DEFENSIVE**
      - **.FISHERY PROTECTION**
      - **.MINE SWEEPERS**
      - **.PATROL BOATS**
      - **.SUPPLY BOATS**
      - **.HOVERCRAFT**
      - **.TUGS**
      - **.SURVEILLANCE**
  - **COMMERCIAL**
    - **POWER**
      - **.INSHORE FISHING**
      - **.DEAP SEA FISHING**
      - **.WORKBOATS**
      - **.PILOT LAUNCHES**
      - **.SERVİCE BOATS**
      - **.LIFEBOATS**
      - **.BARGES**
      - **.INLAND CANALS**
      - **.FERRIES**
      - **.RESEARCH**
      - **.LAUNCHES**
      - **.CATAMARANS**
      - **.SUBMERSIBLES**
      - **.S.W.A.T.H.s**
      - **.DREDGERS**
      - **.HARBOUR TUGS**
      - **.OCEAN TUGS**
      - **.SALVAGE TUGS**
    - **SAIL**
      - **.CARGO**
      - **.BARGES**
      - **.TRAINING**
      - **.RESEARCH**
    - **SKIMMERS**
      - **.HYDROFOILS**
      - **.HOVERCRAFT**
      - **.INFLATABLES**
      - **.RESEARCH**
      - **.WAVE PIRCERS**
      - **.S.E.S.**

Table 2.1. Small crafts-naval and commercial crafts (Tekoğul and Neşer 1997)


ARUP ©

Figure 2.2. Motor yacht. WEB_2 (2004)

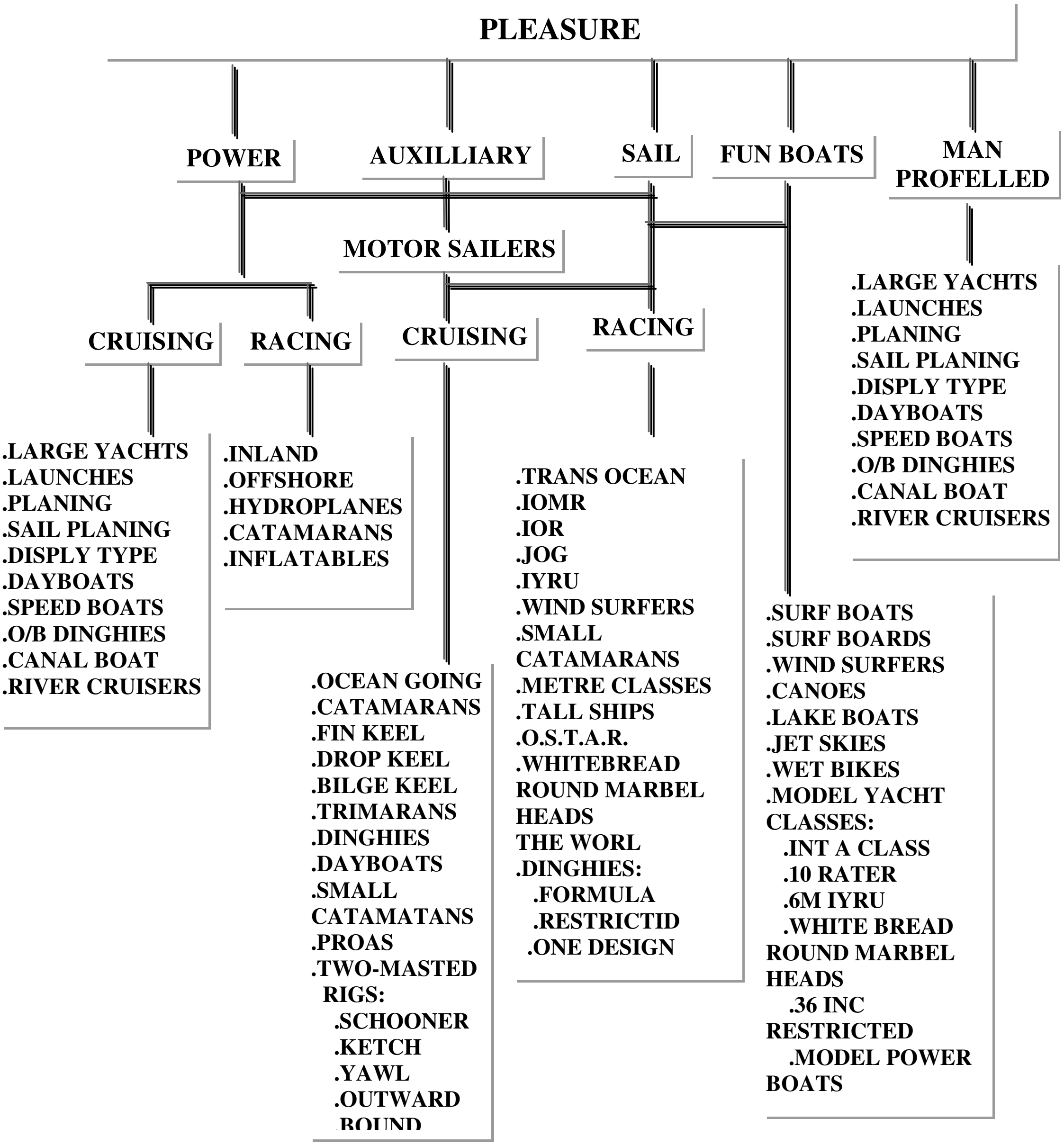


Table 2.2. Small crafts-pleasure crafts (Tekoğul and Neşer 1997)

Figure 2.3. 136' Mediterranean Yacht Yara. WEB_14 (2004)

2.2. Characteristics of Vessel Design

Some significant characteristics of the vessel design process can be identified as follows:

- **Multidisciplinary nature of design -** The problems associated with the design are multidisciplinary, dealing with different aspects such as structure, form, stability, mission requirements, hydrodynamics etc.
- **Iteration -** In any design activity there must be assessment of performance in relation to the purpose and objectives of the design. A measure of the error and recognition of required corrections of the proposed design are required to reach the final design result.
- **Multiplicity of solutions -** There can be many solutions to a given design problem, all of which may achieve the objectives, and may be technically and economically feasible.
- **Multiplicity of objectives -** The criteria for identifying the best design cannot always be reduced to a single type of measure and many different objectives with different measures may be used in the specification. Furthermore, the assumed measures of merit may not be equally important to the final design.
- **Boundedness -** Creative endeavor cannot be allowed to develop indefinitely in any direction. If it is to be feasible it must be contained within those areas, which are judged to bring value, and provide solutions, which are permissible, sensible and susceptible to manipulation. Boundaries, or constraints, need therefore to be prescribed within which the important parameters of the problem may be manipulated to improve the design. Within the boundaries, the effect of the parameter changes upon the fulfillment of the objective should be measurable in terms of value or benefit.
- **Approximation -** The process of creating and evaluating a model does not always follow well-formalized rules with exact theoretical bases. Very often relationships of an empirical nature are used. Furthermore, in any particular design process, the sequence of using relationships and

> indeed the relationships themselves may change. Therefore, the results produced are approximate. As the design proceeds the accuracy should increase provided the methods of assessment used reflect the increased complexity and detailed definition of the design. (Kiss 1980)

2.3. Design Requirements

The starting point for a design is a given set of requirements concerning the vessel type, speed, payload, range, and operating conditions. The termination of the total design task occurs when the design definition embraces both the needs of the customer and the designer's criteria of technical acceptability. The customer objectives will naturally be different for each case. The way they change, from one contract to another, will influence the designer and the decisions he must make. The most basic requirements that any marine vehicle must satisfy are as follows:

1. The vessel must have sufficient buoyancy. That is the displacement of the vessel should be equal to the total weight.

2. The vessel must be buildable and must also be economic to build and operate within practical limits.

3. The vessel must be sufficiently stable and not to capsize in waves that are likely to be met in the operational area.

4. The vessel must have structural integrity sufficiently strong to prevent any damage to vessel itself and passenger or cargo on board.

5. The vessel should be made as sea kindly as possible, i.e. It should be able to operate without excessive motions in waves.

6. The vessel must be safe against damage from fire, explosion, collision or grounding. Sufficient lifesaving equipment must be provided for crew and passengers.

7. The vessel must be controllable and should have sufficient power to make a forward speed.

8. The vessel must be self-sufficient within voyage period. This period may range from minutes to months depending on the type of vessel.

2.4. Design Spiral

The design of a vessel is an iterative process, in which early estimates are made, and then repeatedly corrected and developed as a consequence of feedback from subsequent steps. The multifunctional nature of vessels, they have many conflicting requirements, which have to be met to some degree. Thus the design problem is one of achieving a balanced and adaptable solution, in which uncertainties have been minimized. There is no generally accepted sequential approach to represent the boat design process. Inevitably, however, the adopted process encompasses making a large number of decisions, with each decision or choice greatly affecting the next phase of the design. The adopted process is often repeated with a greater degree of accuracy. The classical way of describing the progressive convergence of the design process to a final configuration is a ***design spiral***. The design progresses in an orderly fashion through a system of processes that address each aspect of boat geometry and boat performance. Within the design spiral concept, the iterative boat design process is considered as a sequence of moves, which gradually define the detail, and thus achieves a balanced conclusion. Figure 2.4. shows design spiral which is used in each phase of designing to reach the balanced design.

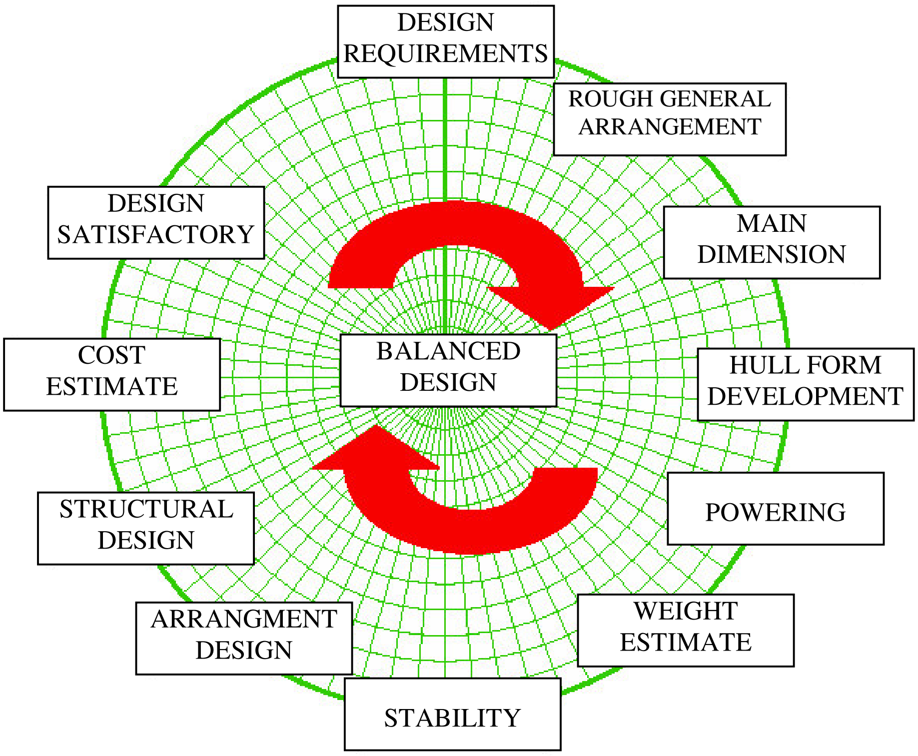


Figure 2.4. Design spiral. WEB_11 (2004)

2.4.1. Process of Design Spiral

The design spiral process starts with a large number of design requirements which includes items such as:

- Maximum Payload Weight
- Required Payload Volume
- Range at Cruise Speed
- Cruise Speed
- Speed/Time Operating Profile
- Design Margins and Standards.

After determination of design requirements, the spiral progress starts and the main dimensions of a particular design are set as step 1.

At Step 2, the user specified dimensional information from Step 1 is combined with other user specified hull form characteristics to establish an initial estimate of the hull form. This hull form includes a simplified 3-D wireframe of the entire boat's hull from baseline up to the main deck level. In order to do this, it is necessary to make an estimate of the full-load displacement on the first iteration around the design spiral. Subsequent iterations around the design spiral will use the calculated full-load displacement from the previous iteration for hull form development. The wireframe defines the geometry of the hull in sufficient detail such that a table of offsets is generated from which faired lines can be readily developed.

Some of the primary output from this step includes:

1. The number of decks in the boat hull and total volume available in the boat's hull and
2. Total area available on each deck.

At Step 3, the resistance and seakeeping of the hullform which was established in Step 2, are calculated.

At Step 4, the entire propulsion system is designed. This includes the design of the propulsion(s), the power transmission, the propulsion prime mover(s) and associated systems. The propulsion system can be either a mechanical drive or electric drive system. The propulsion machinery is sized to match the most demanding speed/sea state case from Step 3.

At step 5, the propulsion system characteristics (power consumed, fuel flow, rpm, etc.) are evaluated at the remaining "off-design" speed/sea state conditions specified by the user. The electrical systems, auxiliary system and outfitting are designed.

The boat's structure is designed in Step 6. Here, both local and global loads are calculated and used with material properties for sizing the structural scantlings for adequate strength. These scantlings are used to estimate the weight of the boat's structure.

At Step 7, Weight Estimates, the calculated weights of all the boat's systems and subsystems are added together to establish a calculated lightship weight. Subsequently, all boat's loads are calculated and summed together.

The boat arrangements are organized in Step 8. The required deck area and volume necessary to support all of the boat's systems and loads are calculated and compared with the volume that is available in the boat's hull. If the ship's hull does not contain sufficient volume to satisfy the volume demand, the volume deficit is made up by increasing the size of the super-structure until the sum of the volume available in the boat's hull and super-structure equals the total volume required.

At Step 9, the intact stability of the generated design is assessed. This analysis uses the 3-D wireframe, developed in Step 2 to evaluate the righting arm throughout the heel angle range of 0 to 90 degrees. The area ratios and metacentric height calculated in the stability analysis are compared with the corresponding standards.

Step 10 determines if a balanced design has been reached. Here, the full-load weight that was used to establish the hullform in Step 2 is compared with the full-load weight that was calculated in Step 7.

If these two weights differ, then another iteration around the complete design spiral is performed, wherein; the hullform calculations are performed using the full-load gross weight calculated in the previous iteration. This iterative process is repeated, typically more than 15 times, until such time as the calculated full-load displacement at the end of iteration is within 0.5% of the full-load displacement that was used at the start of the iteration. (Kiss 1980)

Once the balanced design has been established, the seakeeping behavior, the acquisition and the life-cycle cost of the design are determined, leading particulars of the design are printed. In most cases, subsystem weights are calculated and reported in the output at the three-digit level of detail.

2.5. The Design Process

The first step in boat design process is to define very clearly the main function or purpose of the boat. This called as the design statement. Without a clear idea of how the boat will be used, designer will not be able to adequately resolve the many conflicting choices that will confront him/her during the design process.

Decisions must be made often with very incomplete or approximate data or guesses. The designer must fully recognize where these exist and the resulting limitations and risk so that improvements and refinements can be made later in the design process. There is never a single approach or correct answer in design problem. There is only a best or good, acceptable solution, which balances all considerations.

“The vessel design process can be described in terms of the major design milestones or in terms of the technical evolution as indicated by a design spiral. This process should be a rational development from the perceived needs of the customer to the final design description.” (Kiss 1980) The process may be summarized as consisting of the following steps:

- Design Statement (Needs Analysis and Functional Requirements)
- Concept Design Stage
- Preliminary Design Stage
- Contract Design Stage
- Detailed Design Stage

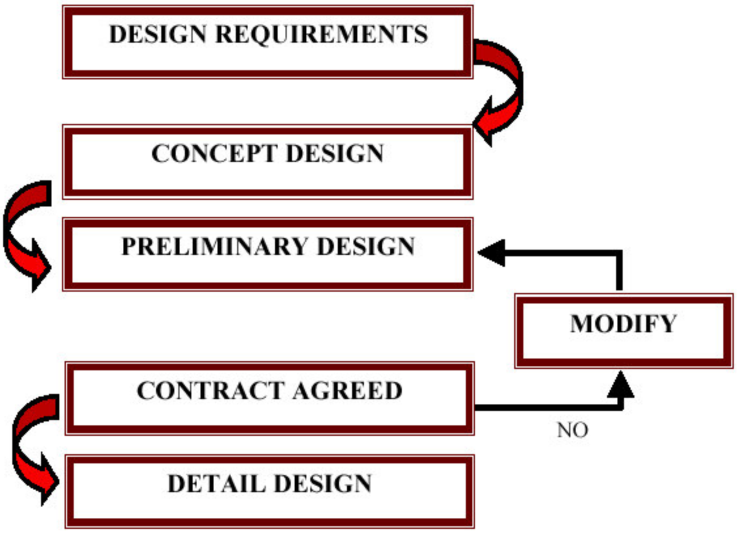


Figure 2.5. Vessel design process scheme. WEB_11 (2004)

2.5.1. The Design Statement

The Design Statement is a short document, which is used to clarify the purpose and goals of the vessel. It is also used to determine the requirements of the owner and to guide the designer in making rational choices between design trade-offs during the design process. A Design Statement consists of the following parts:

1. **The Purpose or Mission of the Vessel**
2. **A Measure of Merit for the Vessel**
3. **The Owner's Design Requirements**
4. **The Design Constraints**

2.5.1.1. The Purpose or Mission of the Vessel

The purpose or mission of the vessel should be defined using one sentence or paragraph. For a successful design to determine the mission of the vessel is a necessity. For example, a mission statement for a commercial passenger vessel might be:

"A boat designed to carry passengers between Karşıyaka and Balçova in a fast, safe, and comfortable manner that will maximize profits over the life of the vessel."

This statement emphasizes speed, comfort, and safety without disregarding the need to make a profit. Any specific owner's requirements or limitations can be defined later, in one of the subsequent parts of the design statement. A simple mission statement like this is important to keep the designer (and owner) focused on the overall purpose of the boat and to help with the resolution of the enormous number of design trade-offs that will be evaluated.

A mission or purpose statement for a pleasure vessel might be:

"A coastal cruising power boat designed for a retired couple to live aboard year-round." (Hollister 1994)

This statement tells the designer an enormous amount about the overall purpose of the boat with a few words. There is a temptation to include many of the requirements and limitations here (such as speed and range), but the goal here is to define one or two key elements, which uniquely define the design. In this part it is not to specify the type of engines, the size, or the cost, unless they are major design constraints.

2.5.1.2. A Measure of Merit for the Vessel

Some designers try to translate the purpose or mission of the vessel into an objective, mathematical equation. This **measure of merit** is a specific formula that converts the complete design into one number, which tells the designer if boat design "A" is better than boat design "B" and helps designer select between major design trade-offs.

Measures of merit are possible for all craft, not just for commercial designs where the goal is to maximize profit. For yachts, a specific measure of merit is possible for competitive craft, such as the America's Cup class. Their measure of merit is to win 4 out of 7 match races. This can be converted into a formula, based on the dimensions of the boat and constrained by the class rules, which will predict the elapsed time of a design over the racecourse for a variety of expected wind speeds. For non-competitive yachts, it is possible to define weighting factors for the major design requirements and assign ratings to each one to determine an overall, single number rating for the boat. Although the weighted rating technique is a subjective approach to design evaluation, it can help the designer and the owner better understand different design alternatives.

For boats that cannot be evaluated by a mathematical equation, designer need to determine a set of important design attributes, their weightings, and their ratings. This is done as follows:

1. Determine a list of major design attributes such as cruising speed, range, ease of operation, cost, comfort, etc.
2. Determine a weighting number for the attribute, which relates the relative importance of that attribute compared to other attributes.
3. For each concept design alternative, assign each attribute one of the following ratings: Excellent, Very Good, Good, Satisfactory, Poor, Unacceptable
4. Apply a percentage value to each rating, for example: Excellent 100%, Very Good 75%, Good 62.5%, Satisfactory 50%, Poor 25%, Unacceptable 0%
5. Multiply the rating percent times the weighting factor for each attribute and sum the result.

6. This single sum value is the measure of merit of the vessel. Designer may wish to divide this number by the best rating a boat could receive so that all scores are between 0 and 100.

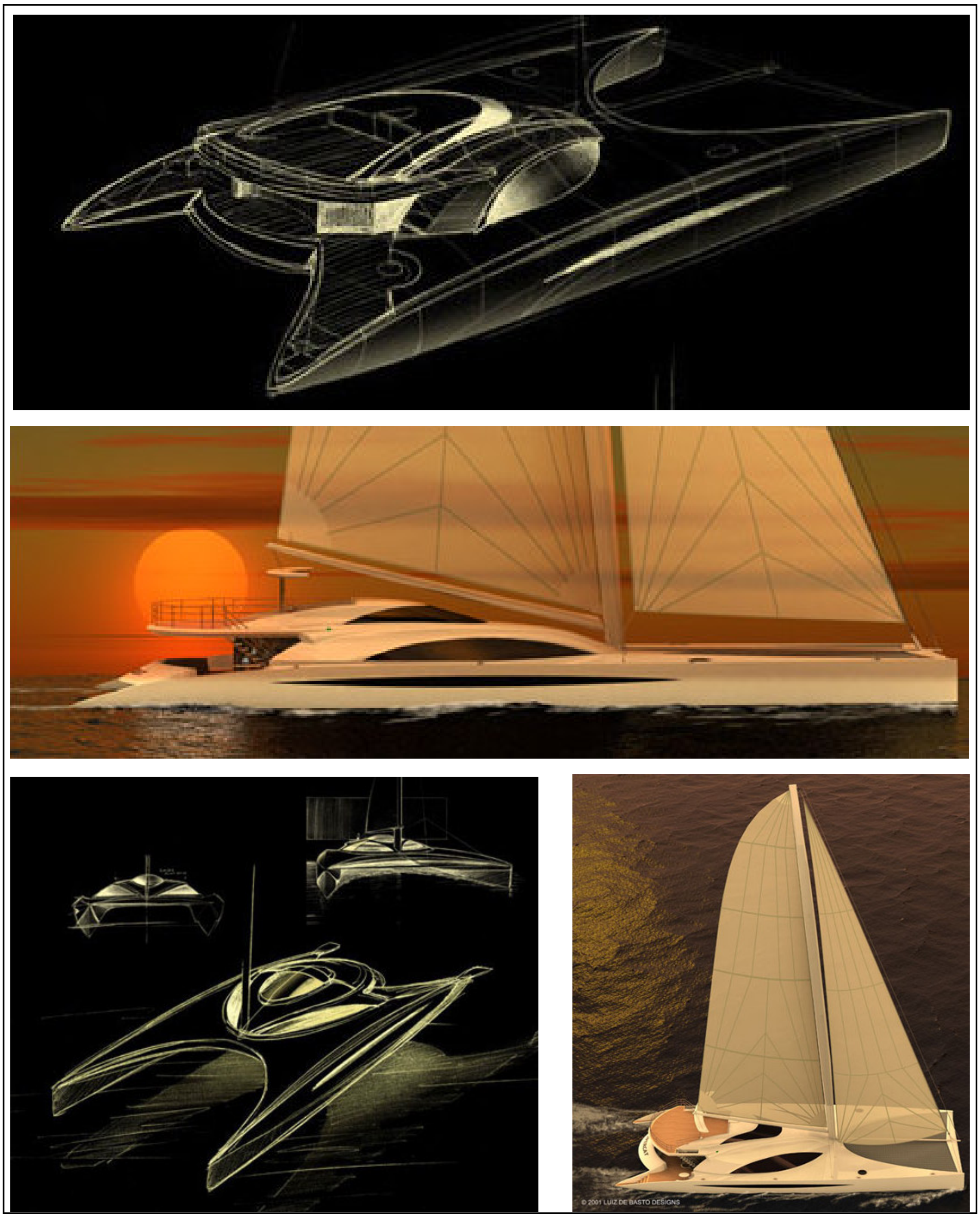


Figure 2.6. Super Cat 110 ' Design for a high-speed cruising sail catamaran. WEB_14 (2004)

A simple weighted rating example for comparing two powerboat designs might look like this:

DESIGN A

Attribute Weight Rating Weighted Rating
Cost 250 Good (62.5%) 156.25
Beauty 200 Very Good (75%) 150
Size/space 150 Excellent (100%) 150
Arrangements 150 Excellent (100%) 150
Comfort 150 Excellent (100%) 150
Ease of Operation 150 Good (62.5%) 93.75
Maintenance 150 Satisfactory (50%) 75
Cruising Speed 100 Satisfactory (50%) 50
Range 100 Satisfactory (50%) 50
……………..
Maximum Rating = 1400 Rating for Design A 1025
Measure of Merit Rating for Design A as a percentage = 1025/1400 = 73.2%

DESIGN B

Attribute Weight Rating Weighted Rating
Cost 250 Excellent (100%) 250
Beauty 200 Very Good (75%) 150
Size/space 150 Very Good (75%) 112.5
Arrangements 150 Very Good (75%) 112.5
Comfort 150 Very Good (75%) 112.5
Ease of Operation 150 Good (62.5%) 93.75
Maintenance 150 Satisfactory (50%) 75
Cruising Speed 100 Satisfactory (50%) 50
Range 100 Satisfactory (50%) 50
……………..
Maximum Rating = 1400 Rating for Design A 1006.26
Measure of Merit for Design B as a percentage = 1006.25/1400 = 71.9%

This example analysis says that Design A, rating 73.2% is a "better" boat than Design B, rating 71.9%. All of these numbers are subjective and can be manipulated to create any result designer want. The goal, however, is to be consistent in designer's subjectivity so that designer can work toward an optimal design.

2.5.1.3. Owner's Design Requirements

Most boat owners specify a target cost, speed, cruising range, and some description of accommodations for the boat. This section of the Design Statement consists of any or all of the following parts:

A. A list of design requirements and their values or ranges are listed in decreasing order of importance.

B. A checklist of design options, assigning each a desirability factor.

C. An owner's description of exactly how the boat will be used.

D. Pictures and descriptions of other boats and options important to the owners.

A. List of design requirements in decreasing order of importance

Firstly, designer must list all major design attributes and assign them some ranking or level of importance. Some sort of target value or range can also be applied to each requirement. For example, most powerboat owners specify a target cost, speed, cruising range, and some description of accommodations for the boat. Thus the designer tries to fix as few requirements as possible, since the best design might involve an unusual or unique combination of design variables. For the pleasure boat example, the owners might list the following requirements:

1. Tug style motor yacht (about 40')

2. Cost (less that $200,000)

3. Easily handled by two people

4. Cruising speed of 8 knots

5. Cruising range of at least 1000 miles

6. Large owner's stateroom with private head and shower

7. Comfortable guest stateroom with private head and shower

8. Very easy to maintain

B. A checklist of design options assigning each a desirability factor

In this section a design checklist is presented to owner. Then owner must review and mark with one or more of the following "Design Option Classifications".

Owner's Design Option Classifications

1. Must Have (MH)

2. Very Desirable (VD)

3. Desirable (D)

4. Desirable, if there is Enough Room (DER)

5. Desirable, if there is Enough Money (DEM)

The following is a partial example of a checklist for the owner to evaluate preferences in equipment and systems and mark each with one or more of the categories listed above (MH, VD, D, DER, DEM). Designer can easily adapt the checklist and classification options to meet her/his own needs.

1. List of optional electronics/Nav station options
   SATNAV, GPS, Loran, Autopilot, Electronic charts, Nav station layout options.
2. Plumbing system options
   Hot/cold water, Pressurized water, Number of heads, Shower, Head/waste system options etc.
3. Galley options
   Stove, Sink, Oven, Galley layout options etc.
4. Electrical system options
   Air conditioning, Desalinator, Television, Stereo etc.
5. Propulsion system options
   Single vs. twin screw, gas vs. diesel etc.
6. Accommodation options
   Number of staterooms, Number of berths, Space requirements etc.
7. Rig Options,
   Roller furling jib, roller furling main, asymmetrical spinnaker

C. An owner's description of exactly how the boat will be used

In this part, the owners describe must be asked. Exactly what they'll do with the boat when it is completed and how it will be used. This can be a written description. This technique conveys the needs of the owner without unduly restricting the designer's options. For the powerboat example, the owners might write:

"When we retire, we will sell our main house and move into our waterfront condo in Stonington harbor, Connecticut. Our boat will be docked at our condo during the summer, where we will cruise extensively the coast to Maine. In the fall, we will cruise the boat along the intra-coastal waterway (ICW) to Florida, where we have a slip in a marina in Ft. Lauderdale and will live on the boat. At some later date, we may decide to leave the boat in Florida during the summer and fly back to our condo in Stonington for the summer." (Hollister 1994)

With a description like this, designer may be able to suggest to the owners a number of design alternatives.

D. Pictures and descriptions of other boats and options

In this section designer asks the owners to show or tell him/her about other boats or design features that they like and explain why they like them. This list can help develop a ranking and weighted measure of merit for the boat. If the designer doesn’t agree with the owner, then he/she can suggest design alternatives and explain the affect of the different choices on the boat.

2.5.1.4. Design Constraints

This section describes all of the fixed constraints, which the design is subjected.

1. Height limits for clearances under bridges
2. Draft limits for shallow water
3. Dock, slip, canal, or lock size limits
4. Rating rule constraints for racing sailboats or powerboats
5. Width and weight limits for trailering on the highway
6. Size or weight to meet U.S. Coast Guard classification

2.5.2. Concept Design Stage

The Conceptual Design Phase determines whether the boat described in the design statement is feasible and how the stated goals in the Design Statement must be modified to achieve a feasible and successful design. It is important for the designer to strive for an optimal design, rather than just a feasible solution. Principal dimensions, general arrangements, major weights items, and powering options are chosen, and concept drawings are produced and included in a concept statement or design proposal which is then submitted to the client or prospective client. This step is often done on speculation in the hopes that a client will select the design for construction.

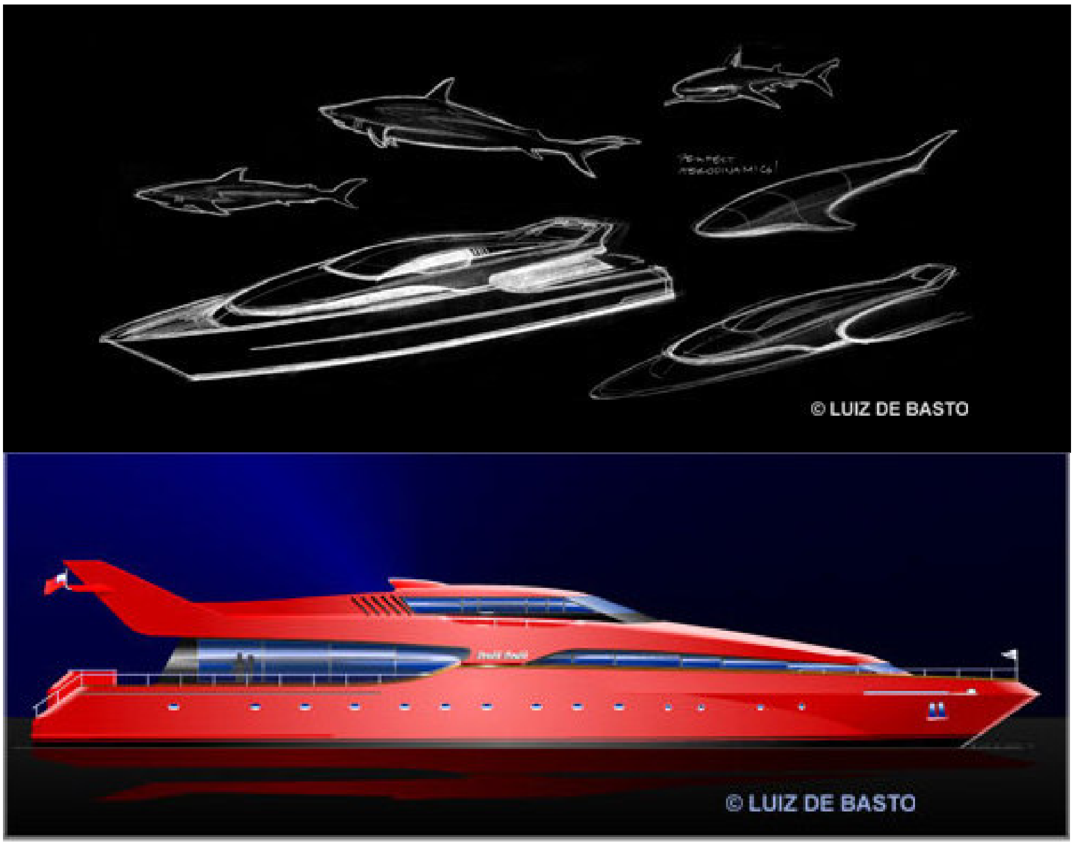


Figure 2.7. 140' tri deck 1995 Concept for a custom Motor yacht. WEB_14 (2004)

All designers have their own ways to approach this design phase depending on their experience and the type of boat being designed. Concept Design Steps are as follows:

1. Classify the cost for the new design compared to other boats of the same type

2. Identify all major design trade-offs

3. Select an iterative process, which will create a feasible design

4. Create a measure of merit (analytic or subjective) for the design

5. Optimize the principal dimensions of boat

6. Optimize the details of the boat

1. Classify the cost for the new design

The designer must know the prices, which belong to comparable boats on the market before starting to pick the principal dimensions, arrangements, and performance goals for the boat. Then classify the boat as being in a low cost, an average cost, or a high cost range for this type of boat. This will help to development of concept design cost estimate.

One way to estimate the cost of the boat is to plot cost versus weight and cost versus length for a large group of boats and use these graphs as general guidelines.

Another technique for cost estimation is to assign prices to the different parts of the boat. Designer can even assign price ranges (low to high) for each item to determine a range of prices for the boat. As the design nears completion, this range of prices should narrow.

2. Identify all major design trade-offs

To achieve a feasible design, designer need to make sure that everything fits, the boat floats, and it performs as expected. The interaction of the many interrelated variables must be identified before a design approach can be determined. Some of the common design trade-offs are listed below:

1. Weight, Longitudinal Center of Gravity (LCG) versus Draft, Trim
2. Weight, Hull Shape, Vertical Center of Gravity (VCG) versus Stability
3. Weight versus Structure, Arrangements
4. Volume versus Arrangements
5. Weight, Hull Shape versus Power, Speed

7. Weight versus Cost

Designer must notice that the weights and volumes of the boat are involved with all of the trade-offs: cost, size, flotation, and performance of the vessel. Any significant change to the weight values sets off a chain reaction throughout the design. Some designer thinks that weight analysis plays the key role in boat design. As the weight of the boat goes up, so the costs and the power required to push the boat at a desired speed go up too. It's not current for the desired cruising range, because for them the critical point is to reduce the weight and volume of engines and fuel tanks, but to increase the power requirements are more important. Defining and tracking accurate weight estimates for the boat early in the design cycle is designer's best tool toward minimizing the design iteration time.

3. Select an iterative process, which will create a feasible design

This phase involves selecting a step-by-step procedure for creating a feasible design using the trade-offs of the last section as a guideline. Every boat has different needs, requires and different approaches to solve their feasibility. Designer must start by examining the major purpose of the boat. For a pleasure boat, the design could be centered on live-aboard comfort and ease of operation. For a racing sailboat, the major goal is to have a fast boat, so hull shape and light weight are emphasized and accommodations are secondary.

The designer firstly must define the feasibility iteration process so that it starts with the most important design attribute.

4. Create a measure of merit (analytic or subjective)

Measures of merit are functions or equations used to evaluate the "goodness" of a design. Some are subjective ratings and some are analytic, based on extensive scientific modeling.

In some cases the measure of merit is obvious, such as for the passenger ferry, where the goal is to maximize profit or minimize the required cost per passenger. For a pleasure boat, the measure of merit is vague and subjective. In most cases, determining the exact formula for the measure of merit is quite complicated. Designer should try to create a measure, because the only alternative is to use his/her intuition, gut feelings, or vague generalities to determine how two boat alternatives compare.

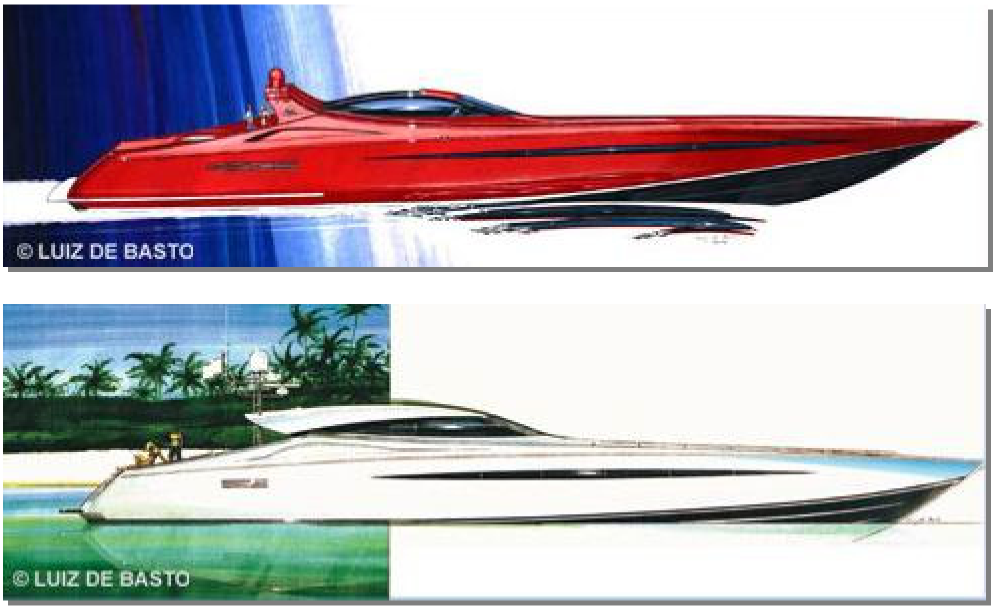


Figure 2.8. Cary 98' two different concept study for a high speed Sport Yacht WEB_14 (2004)

5. Optimize the principal dimensions of boat (Global Optimization)

The most common approach to design optimization is to create several different "concept boats" which have widely varying principal dimensions, such as length, beam, draft, weight, and powering. These concept boats are created after an examination of the purpose of the boat and after performing short feasibility studies on a series of designs.

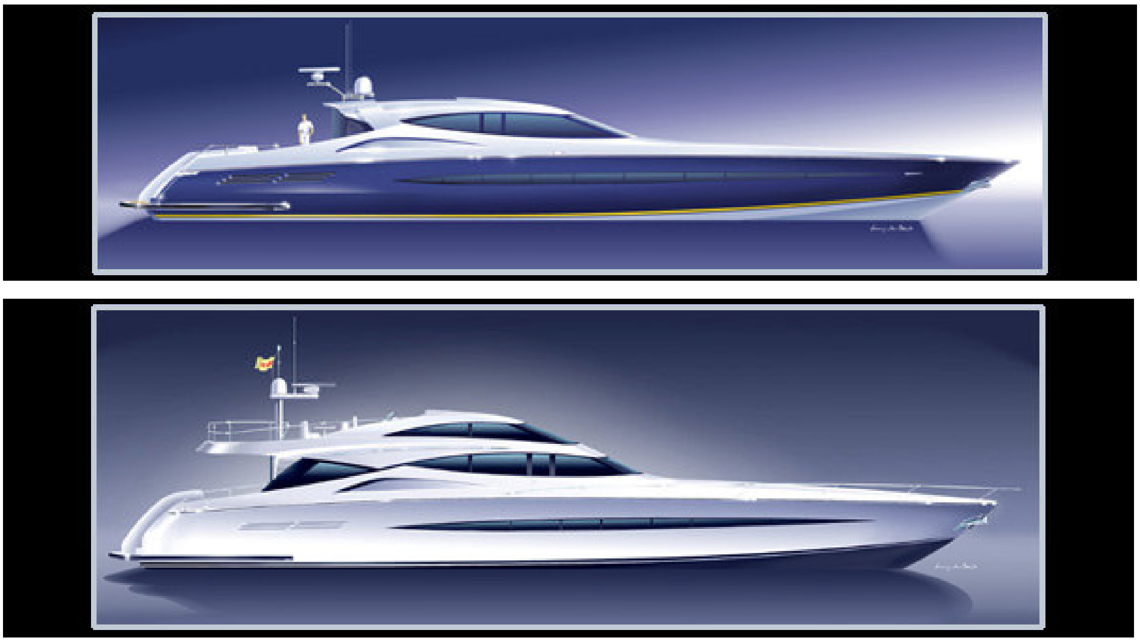


Figure 2.9. Sport yacht - 100' high-speed vessel with different versions. WEB_14 (2004)

6. Optimize the details of the boat (Detailed Optimization)

Once a designer has selected the initial concept boat with the best potential, he/she still may wish to optimize it further. This is the most common approach to design development or evolution. Many designers create new boats simply by varying, customizing, or optimizing their previous designs for a specific purpose or customer. This adaptation and optimization process is done using **educated guesses**, **parametric analysis**, or **automatic optimization**.

a. Educated Guesses

Designers who have the extensive experience can begin to develop a very good sense of what will and will not work on a boat. Always designers have some ideas on how to improve or optimize an existing design, especially if the designer has built the previous boat and he/she has had a chance to evaluate the result.

b. Parametric Analysis

Parametric analysis is a technique whereby all design variables are held constant. As the independent or "free" variable is systematically altered, the designer evaluates the changes to the design using some kind of measure of merit with graphics.

c. Automatic Optimization

It is possible to write a computer program to automate the parametric variation process of searching for an optimum solution. Due to the complexity when used with many design variables, most attempts at this optimization process involve carefully designed problems using the fewest number of free or independent design variables. The designer and programmer limit the number of search variables to a few key design values, thereby fixing the rest of the design variables and assuming that they don't affect the problem. A well-designed optimization problem can lead designer very quickly to the optimum solution of a design trade-off.

2.5.3. Preliminary Design Stage

The preliminary design stage includes early concept formulation through the preparation of plans and specifications that form the basis of a building contract. This stage can be called as pre-contract design. This phase of design is the most significant of the whole design process. It is the stage of design where the major characteristics are determined, the dimensions have become firm, the requirements and the mission have come into clear focus.

If the results of the Concept Design stage are accurate and there aren't any last-minute design changes, designer should not run into any large trade-off problems, which require to re-evaluate whole design concept.

The following steps characterize the Preliminary Design phase:

1. Complete the hull shape definition
2. Perform a detailed structural analysis for the boat
3. Finalize the interior arrangements
4. Determine hydrostatic and stability requirements
5. Re-evaluate resistance, powering, and performance of the boat
6. Calculate detailed weights to determine an accurate draft and trim for the boat
7. Calculate detailed costs for the boat

1. Complete the hull shape definition.

In Concept Design process the initial hull shape is created and refined, but didn't necessarily performed any detailed. During this Preliminary Design phase, the hull shape is further refined and faired for the purpose of calculating more accurate analysis and arrangement results.

2. Perform a detailed structural analysis for the boat.

After the hull shape is finished, designer should determine the required structure for the boat. This information includes the type of building material, the thickness of the material, the location and sizing of all frames, and the location and sizing of all longitudinal stringers. There are a number of ways to determine this information. “The most common method is by using a structural rule defined by the American Bureau of Shipping or Lloyds. They have structural rulebooks for boats such as sailboats, powerboats (high and low speed), and fishing vessels.

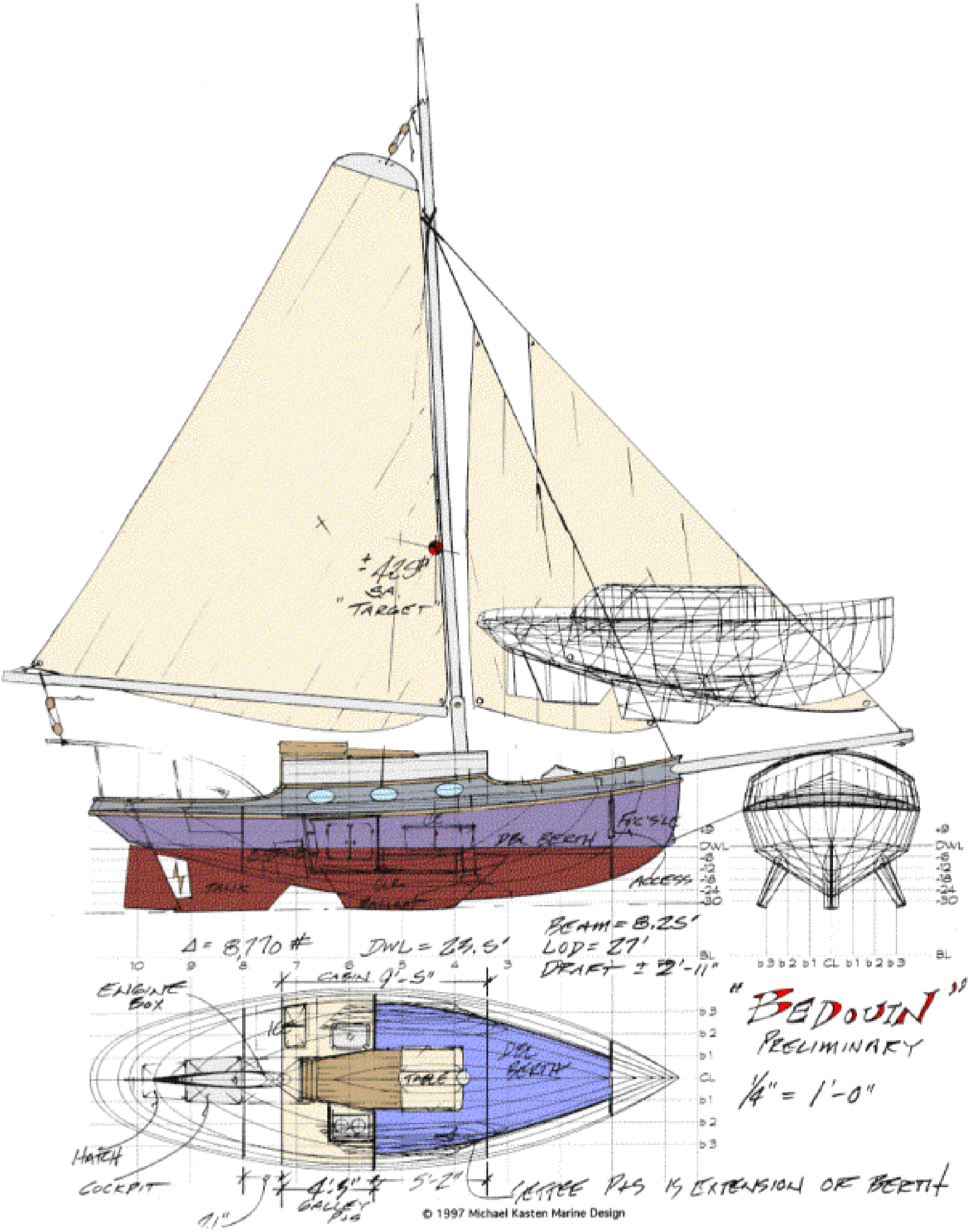


Figure 2.10. Preliminary design study. WEB_13 (2004)

ABS Guide for Building and Classing Offshore Racing Yachts has sections which cover keel bolt sizes, plating thickness, internal structure sizes, and rudder structural calculations. The guide provides all of the equations which designer need to do the calculations for a variety of materials and construction techniques." (Hollister 1994)

If designer doesn't want to be confined to the generic equations supplied in these rulebooks so then he/she will have to develop his/her own methods for determining the forces acting on the hull and the equations to be used to evaluate a variety of plating and internal structural arrangements. The hull structure must provide both overall longitudinal strength and local impact damage resistance. This is done with a combination of plating material, plating thickness, number and size of frames, and number and size of stringers.

One of the most difficult aspects of structural design is to predict the various types of loads that the hull must withstand: static hydrodynamic pressure, rig forces, dynamic wave impact loads, and dynamic debris impact forces. Another goal may be to create a deck strong enough to support a human without flexing. The deck might be perfectly strong, but it might also flex when walked upon.

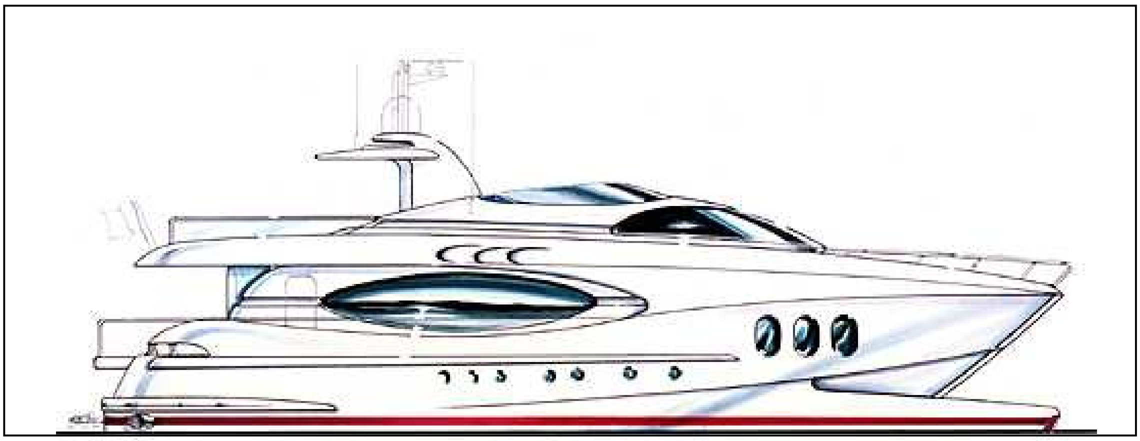


Figure 2.11. 24 meters Motor catamaran exterior . WEB_12 (2004)

3. Finalize the interior arrangements

After the hull shape has been finalized, designer can determine the details of how the interior pieces fit together. Designer must to determine if everything will fit as expected, or if there is something that was overlooked.

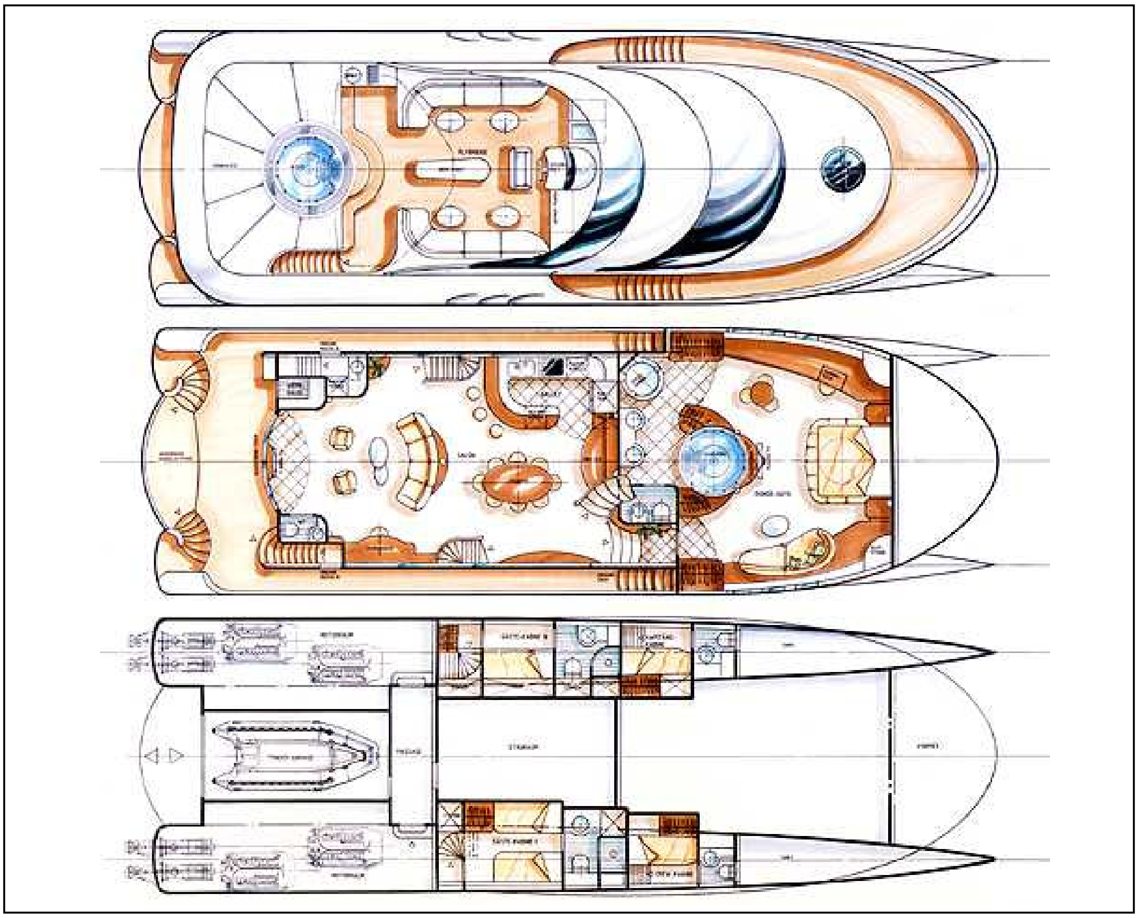


Figure 2.12. 24 meters Motor catamaran Interior. WEB_12 (2004)

4. Determine hydrostatic and stability requirements

The hydrostatic and stability calculations for the boat are required to determine how the hull shape and boat weights affect the performance and safety of the boat. The hydrostatic (volume) calculation provides information about the hull shape in its upright condition and the stability calculation determines additional righting moment information when the boat is heeled over. For certain types of commercial vessels, the design has to meet specific federal regulations related to freeboards, stability, and floodability.

a. Hydrostatic Calculations

These calculations determine properties of the hull shape for any upright flotation plane. These properties include volume, displacement, center of buoyancy, wetted surface, metacentric heights, and hull shape coefficients. From a design standpoint, there are two ways to approach these calculations:

Method A. Firstly a waterline is given (draft at amidships and trim), calculated the hull properties, including displacement and longitudinal center of buoyancy (LCB), which will equal the boat's weight and the longitudinal center of gravity (LCG). If the designer starts the design process by drawing a waterline on his/her profile view of the hull, he/she can use the draft and trim (usually a boat is designed to have zero or even trim) values to calculate the associated values of displacement and LCB. The displacement value calculated must equal the sum of all of the boat's weights, and the LCB position must match the longitudinal position of all of the boat's weights (LCG). If it doesn't, then either the waterline must change or the weights must change.

Method B. Firstly the displacement and LCG are given, calculated the hull properties, including the waterline (draft and trim). This is the reverse calculation from the draft and trim example. The program must search for the waterline (draft and trim) which matches both the target displacement and LCG (LCG must match the LCB position). If the resultant waterline is not appropriate (too high/low or it has too much trim) then some of the weights and/or their positions must change or the hull shape must change.

Most designers start by selecting a target displacement for the boat. This target displacement is determined by experience and by evaluating similar designs. From this target, the designer modifies the shape of the hull to match the target displacement and modifies the weights to achieve the target displacement. To match the trim the weights are adjusted or the hull shape is modified by shifting volumes. The target displacement usually includes an over-weight contingency factor of between 5 to 10 percent. This means that there is a normal tendency for the boat to be built heavier than expected.

As designing the boat, designer may find that the longitudinal center for the weights (LCG) does not match the longitudinal center of buoyancy (LCB) for the no-trim, even-keeled waterline that he/she drew for the boat. This means that the boat will trim down by the bow or stern until the center of buoyancy (LCB) shifts to match the position of LCG. For correcting this problem, designer must either shift weights or change the shape of the hull as follows:

A. Moving weights

If the boat is down by the bow, shift weights aft

If the boat is down by the stern, shift weights forward

B. Changing the hull shape

If the boat is down by the bow, shift the LCB forward (add volume forward)

If the boat is down by the stern, shift the LCB aft (add volume aft)

b. Stability Calculations

The stability calculations determine information related to the safety and comfort of the boat. Given an upright draft and trim, the stability calculations determine the righting moment for any heel angle. This process is done by heeling the boat to the desired angle and then letting it sink and trim until the heeled displacement and LCB matches the upright displacement and LCB. The righting moment (or righting arm, since righting moment is equal to the product of righting arm and displacement) is then plotted for all heel angles from 0 to 180 degrees. The initial stability of the boat is related to the slope of the curve at a heel angle of zero, and the area under the curve is related to the dynamic stability of the boat. Two other important points are the heel angle of maximum righting moment and the heel angle at which the righting moment goes to zero. Sometimes it is desirable to plot a heeling moment curve on top of the righting moment curve. Examples of heeling moment are wind heel and passengers or cargo located off-center.

Rules created by various regulatory bodies (such as the Coast Guard) use a combination of these values to determine if a design has sufficient stability.

For certain commercial vessels, regulatory bodies also require that additional criteria for damaged or flooded conditions be met. One criterion is called a "floodable length" condition, which requires the boat to remain afloat (in an upright condition) after one compartment is flooded side-to-side. Another criterion is called one- or two-compartment floodability, where the boat must remain afloat and stable after any combination of one or two compartments are flooded. There are special computer programs, which can be used to define and flood arbitrarily shaped interior compartments. These programs are only needed for those boats required to meet the stringent regulatory conditions.

5. Re-evaluate resistance, powering, and performance of the boat.

After the hull shape is completed designer can re-evaluate the performance of the boat. The techniques and programs used to evaluate powerboats and sailboats are quite different because of their characteristic.

a. Powerboat Resistance and Propulsion

Powerboats are classified as either displacement-type or planing-type vessels with their performance specified in terms of cruising speed and range. Although there are different methods for calculating the resistance of each type of vessel, the powertrain components are still the same. All powerboats consist of the engine, reduction gears, shafting, auxiliary devices, such as generators, and a propulsor, such as a propeller or waterjet. The design objective is to select the components that produce the required thrust to push the boat at the desired speed with the greatest efficiency. The problem can be complicated by the need to maximize the efficiency even when the boat is operated at a range of speeds.

b. Sailboat Performance

All sailboats must be seaworthy, stable, have a good balance and perform well for their intended purpose. The key is that all sailboats have different purposes and goals. A cruising sailboat may not be optimized for speed, but it should move well through the water and be easily controlled.

6. Calculate detailed weights

Before determining the detailed weights for the boat, the hull, the structure and the hydrostatic calculations must be accurately completed. Otherwise they might have to be changed if the total weight from this step doesn't match the displacement and trim found in the hydrostatics calculations. Although many initial weight estimates were done in the Concept Design phase, these have to get as detailed as possible in this phase.

Many of the weight estimates may be obtained by pure guesswork, but hopefully there will be an equal number of overestimates and underestimates.

The importance of generating an accurate weight estimate cannot be overstated because it is the key element in making sure that the design is a success. If a boat is launched and floats below its lines, then the boat won't be its designed speed and the estimated waterline.

If the sum of all of the weights (plus overrun contingency) is greater than the target weight, designer must try to close the weight to estimated weight.

After the Concept Design stage, designer has established the feasibility of the design and of meeting the target displacement. Therefore, if designer are close to estimated weight, he/she should be able to make some minor changes, along with using the contingency allowance, to meet the target weight. If designer's total weight is way off the target weight, then perhaps there is a problem with the Concept Design results. Therefore rather than try to correct the design at this stage and continue on, designer should drop everything and re-evaluate the complete Concept Design results, and not continue until the weight problem is resolved.

7. Calculate detailed costs for the boat

After the Concept Design stage, designer should have enough information to submit a bid request to various builders to obtain an estimate cost for construction.

Designer may wait to submit the bid requests until the end of the Preliminary Design process where he/she has more details on the design or that might delay the Detailed Design process.

Once a builder is selected, designer can then discuss the exact type of information (drawings, specifications, full-size drawings) needed from the designer. To know this information before the designer start to prepare the deliverables in the Detailed Design stage will save him/her a lot of unnecessary work.

2.5.4. Contract Design

Preliminary Design may be thought of as designing the boat, while Contract Design is designing the contract. The goal of contract design is to produce a set of bid documents that will ensure that what is built is what the designer wanted. A contract design package presents the information that the builder needs to bid on the boat. A typical contract design package includes: arrangements drawings, structural drawings, structural details, propulsion arrangements, machinery selection, propeller selection, generator selection, electrical one-line diagram, navigation and communication equipment list, bridge layout, auxiliary steering station layout, piping systems, FW schematic, SW schematic, firefighting system schematic, fuel systems schematic, hydraulic system schematic, waste-sewage schematic, furniture schedule, door list, decorative coatings list and painting system schedule. This information is presented in a stack of drawings and a written specification.

2.5.5. Detailed Design Stage

In the detailed design stage every necessary detail is worked out so that material may be ordered and construction may begin. The members of the detailed design are not necessarily the same as those, which completed the conceptual and preliminary design stages. The nature of the work has now changed significantly as it is directed towards the definition of the boat for contract and production.

Detail design tasks include monitoring of the vessel's weight during construction, updating the trim and stability calculations based on as-built data, development of structural details, final design of the engine foundations including calculation of foundation vibratory frequencies, circuit breaker balance calculations and final decisions on pipe and cable routings.

The Detailed Design phase is that portion of the design involved with producing the design "deliverables": the drawings, the templates, and the specifications. What the designer includes in this design package depends on the needs of the builder. This raises a couple of interesting design process considerations, which must be dealt with well before the designer get to this point in the design. Detail Design Deliverables include: Hull Lines Drawing, Workshop drawings, Three Dimensional Views, General Arrangements, Structural Drawings, Deck Plans, Machinery Equipment and Arrangements and Systems Diagrams. (Written Specifications.)

2.6. Vessel Design Methods

The design process can be carried out in several ways. Traditionally the designer relies upon accumulated experience and data for the type of vessel being designed. He/she focuses on past practice and interpolates from similar existing vessels. Presumably these existing vessels represent optimum or near optimum designs and small deviations would not be economically unsatisfactory.

Alternatively, preliminary vessel design may be regarded as an economic optimization problem with constraints. This allows an overall evaluation of competing design alternatives to be based on systematic variation or optimization. Some of the vessel design methods are presented in the following sections.

2.6.1. Parent Design Approach

In this technique the design is based very closely on a single vessel type. This so-called parent is chosen to possess performance characteristics as close as possible to those demanded by the new operational requirements. Clearly if the designer has a satisfactory and proven basis vessel, and if the new requirements do not entail major departures from it, this may be a reliable and rapid method.

However this method restricts the designer's ability to reflect the customer's needs and his response to changing technology. If the designer is presented with operational requirements that differ radically from those of any previous vessel in his data bank, he/she will be unable to choose his parent vessel with confidence. Therefore, this technique is inappropriate to most modern vessels unless only a small variation in a previous design is entailed.

2.6.2. Trend Curves Approach

The designer initially has only the owner's requirements from which the basic form of the vessel and ultimately the complete design must be developed. At this stage, in order to obtain some range of values for the dimensions, the designer may refer to plots of data gathered from existing vessels. The method has the virtue of not being tied to a single parent ship but it does rely on mean lines through the data. Thus new designs derived using this approach must be compromise between relevant and inappropriate previous designs. It is likely that the new design will be safe and conventional and this latter characteristic may not be appropriate to the design objective.

2.6.3. Computer Applications in Boat Design

Although vessels have been designed and built for a long time, the last few decades have witnessed dramatic progress in vessel design techniques. The most visible changes are the ever-expanding applications of the computer. These embrace not only all levels of technical design and analysis, but also incorporate production and operational considerations in the design process

The computer was first used in marine industry to perform routine design calculations, such as hydrostatics and intact stability, in the late 1950s. At that time the main purpose was to let computers carry out the simple arithmetic operations, and the steps involved were exactly the same as those employed by the traditional hand calculations.

Computer can be used all phase of design such as determination of hull, drawings, to perform a detail structural analysis, to calculate detailed costs for the boat, to evaluate resistance, powering, and performance of the boat and interior arrangements etc. Besides using computer for design process, computer can be used for the production process with the full 3D computer model of the boat.

CHAPTER 3

MATERIALS USED IN BOAT CONSTRUCTION

The building material from which the vessel is to be built has, of course, a most importing effect on design and production. There are various advantages and options available to the designer of each material.

Recreational boats have been manufactured from many different materials, including steel, ferrocement, wood, aluminum, thermoplastic materials and FRP.

The most common material used in recreational boat manufacturing is FRP. This material has gained acceptance in recreational craft industry because of its unusual characteristic such as lightweight, vibration damping, corrosion resistance, impact resistance, low construction costs and ease of fabrication, maintenance and repair. Beside these unique properties of FRP, it's also suitable material for serial production of boats, especially with the developments in the area of material and construction techniques.

This chapter addresses the boat building materials, material characteristics and comparison between materials to choice the material which is suitable for recreational boat design and serial production techniques.

3.1. Steel as a Boat Building Material

Steel is an excellent material for construction where low cost is paramount. It is the least costly materials for a one yacht or work boat about %20 less than wood construction and as much as 40% less than aluminium. Another big advantage of steel is its strength. It is the strongest of all the common boatbuilding materials, and has a tensile strength of about 55,000 pounds per square inch. (Brewer 1994)

Steel is the principal material used in hull construction of large ships. Ships-fishing and merchant over 50m length- are exclusively constructed of steel. However, in the construction of vessels of smaller dimensions, four other materials appear (wood, FRP, ferro cement, aluminium) and at a vessel length of about 10m steel is rarely used as hull constructional material. There are several reasons for this. A steel hull is a structure of very large volume with a relatively thin skin (outside shell) but the minimum thickness of this skin is limited to about 2-3mm in order to provide resistance against distortion by shock (bumping against an obstacle like another boat or harbour quay). Steel is liable to corrosion and the thinner the plate or profile the faster it is destroyed by corrosion and must be replaced. The weight of steel vessels is also comparatively high for small vessels in proportion to wooden and especially FRP vessels. Therefore, steel vessels tend to appear at a size corresponding to about 12m length, however, in tropical environments where corrosion is an even greater problem: this lower limit is frequently raised to 15m or more.

Shipbuilding steel must conform to special requirements; it must be appropriately tested and approved before it is used for construction of vessels. It is a material combining relatively high strength with elasticity and durability. It can be electrically welded which nowadays is the usual method of joining parts of a steel hull structure together. Steel hulls may be prefabricated in section, which is very advantageous from the point of view of labour and material costs.

The steel hull structure of a vessel consists of rolled plates and profiles. Plates appear in different size (length and breadth) and different thickness. The thinner plates (3-6mm) are mostly 5 to 8m long and from 1.2 to 2m wide. Thicker plates (up to 30mm and more) are up to 12m long and 2.5m (sometimes 3m) wide. It is important when planning shell and decks plating that standard sizes (size which are normally produced by the particular steel works) are used wherever possible. Ordering steel outside these sizes will involve extra costs. The thicknesses are mostly sub-divided by half millimetres (3, 3.5, 4, 4.5, etc). For greater thickness (over 20mm), however, the difference is one millimetre. (Traung 1978)

Profiles used in vessel construction are simple flats, bulb flats and angles. V and I profiled sections are seldom used but round bars and pipes appear as pillars and other items of the hull structure.

3.2. Ferrocement as a Boat Building Material

Ferrocement can be considered similar to reinforced concrete in-so-far as it uses a cement and aggregate binding material surrounding a reinforcing steel armature. The essential difference between ferrocement and other form of reinforced concrete is in the use of fine-grained aggregate and fine mesh reinforcement in a thin shell structure.

These ingredients result in increased flexural and shear strength and a resistance to corrosion of the reinforcing steel due o the restriction of crack widths to below critical values above which moisture could enter the shell structure. The high proportion of small diameter wires in the mesh increase specific surface, improving tensile bond capacity and inhibiting cracking in the mortar matrix. A dense fine-grained mortar is also required to ensure a low absorbency and corrosion is further inhibited by the alkaline environment of the cement rich mortar.

Substitution of mesh by short wire fibre reinforcement to control cracking, in combination with high tensile wires to resist tendon forces is a further development which, when compared with mesh reinforced ferro cement, is claimed to have a favourable cost strength ratio with substantial increases in strength and reduction in crack width.

The properties of the mortar which goes into the fabrication of ferro cement is dependent upon a number of important variables. The specification of the mix design should include:

- Water: cement ratio by weight
- Sand: cement ratio by weight
- Grading, shape, source, purity and chemical composition of sand
- Quality, age and type of cement
- Quality of water
- Type and amount of admixtures

The ultimate quality of mortar is highly dependent upon its application. The available information should include:

- Type of mixer
- Mixing time
- Estimate of the type and amount of vibration or compaction
- Environment at time of mixing (wind, humidity, temperature)
- Curing (temperature, duration, type).

There is no doubt that a high compressive strength positively influences the optimal mix characteristics. The higher the concrete compressive strength, the sounder the more durable the hull.

The mix should be designed to obtain maximum compressive strength and should have the general proportions of one part of cement to two part of sand, with

0.38-0.4 parts of water. The slump obtained by a standard slump test should be 50-60mm.Test cylinders should be taken and minimum compressive test of not less than 420 kg /cm² (6,000psi) should be obtained. The specification of a mix design should include:

Cement: which should preferably be Type II Portland or Type V rapid hardening cement to a suitable specification such as ASTM 150-70 T or BS 12 containing not more than 10% tricalcium aluminate; cement to be of fresh fine quality with no lumps and should be used as quickly as possible after ordering.

Sand: which should be substantially quartzitic with grain size not exceeding 2mm and fit the following size envelope:

ASTM sieve size 7- 100% passing
ASTM sieve size 15- 80-90% passing
ASTM sieve size 25- 60-75% passing
ASTM sieve size 50- 15-40% passing
ASTM sieve size 100- 5-20% passing
ASTM sieve size 150- 0% passing

If quartzitic sand is not available alternative sands may be used, subject to a satisfactory size envelope and adequate compression strengths being obtained.

Water: which is to be clean and free from materials in solution, which could affect the strength and resistance of the mortar. The water / cement ratio is to be of the order of 0.38-0.4 and additives can be used to obtain the desired ratio, while retaining sufficient plasticity to ensure penetration. Choice of additive should be limited to type and quantities appropriate to the construction of thin shell concrete; other additives required for suppressing undesirable reactions between certain cement formulation and reinforcement materials may be desirable, depending on chemical composition of cements available locally. (Traung 1978)

3.3. Aluminum as a Boat Building Material

Aluminium is one of the finest materials for boat building. Weight saving and resistance to normal forms of surface corrosion are major factor in the choice of this material for vessel construction. Resistance to normal forms of surface corrosion in aluminium is based on the presence of a thin, compact, hard surface film of aluminium oxide which thickens with time and when scratched builds up a new protective film.

Pure aluminium containing 99.5% or more and minimal amounts of silicon and iron has the highest corrosion resistance of all aluminium alloys. As this is too soft for applications in ships, aluminium is alloyed with magnesium, manganese and silicon for marine application, these alloys also containing minimal amounts of copper and iron. The work-hardened aluminium-magnesium-manganese-group of alloys show the best resistance to seawater corrosion. Generally speaking, the higher the magnesium content in marine aluminium, the higher the strength, although 5.5% Mg is the upper practical limit, both from a corrosion point of view. The heat-treatable alloy 6601 (1% Mg to 0.6% Si) has generally proved satisfactory, although somewhat less corrosion resistant than the above marine aluminium. The heat-treatable alloy 8351 (0.6% Mg to 1% Si) used in extruded form for beams, etc, has acceptable corrosion resistance and higher strength than 660. (Traung 1978)

Despite resistance to most forms of corrosion common in other materials, pitting corrosion can occur in corrosive atmospheres where dissimilar ions are present on the surface of the metal. Under normal conditions this form of corrosion reduces with time and is self-healing. A much more serious form of corrosion is due to galvanic action between dissimilar metals in the presence of liquid electrolytes (eg, water containing dissolve salts). Contact between metals far apart in the galvanic series can result in rapid corrosion.

3.4. Wood as a Boat Building Material

People have built, paddled and sailed boats for tens of thousands of years. Throughout that time, almost all water craft have been built of wood.

Wood is an organic material that has lengthwise cells and cell membranes, made of cellulose. Kind of wood and its properties are very important in conventional wooden boat building. It has to be chosen disinfected woods free of harmful organisms in this method. However, it is very important to use natural resinous wood. Natural resin protects the wood against to the environmental effects and harmful organisms. (Tekoğul 1986, Kahraman 2000)

Mechanic properties of wood depend on some factors. These factors are climate, territory, wind, growing faults, cutting time, age and environment. The other properties of wood were listed below in categorized by advantage and disadvantage:

The advantage of wood material:

1. It provides comfort and aesthetic. It can be used as a main building and decoration material. Processing is cheap and easy by simple organization.

2. Its heat conductivity is bad. It is obtained heat isolation by using wood in boat.

3. Its density changes between 0,31 – 0,72 ton/m³. Its density is average 0,60 ton/m 3. So, it is a light material and its strength/density ratio is high.

4. Its broken resistance against to material fatigue is very high. When wood can keep 60% of broken resistance, aluminium can keep its 40% and fiberglass can keep its 20% broken resistance after it was applied load 1 million times regularly.

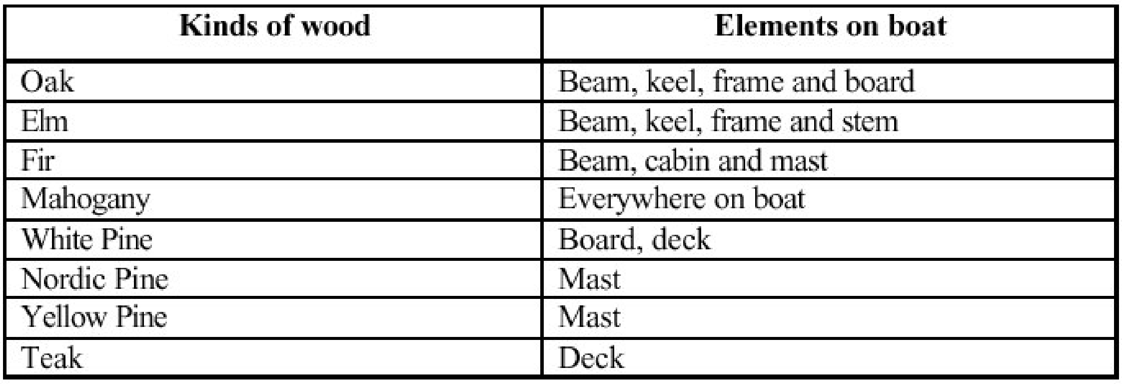
The disadvantage of wood material:

1. Cells of wood are permeable. Wooden material expands and shrinks by temperature and moisture. If moisture rate in cells increases, wood strength decreases.

2. Wood's surface has to be painted or covered by vanish against to some harmful organisms and moisture that cause decay in wood.

3. Wood's life changes between 6 – 16 years.

4. Mechanic properties aren't the same everywhere on the wood. Longitudinal and latitudinal directions of wood's strength aren't same. This variation is an important problem for wood user. (Tekogul 1986, Kahraman 2000)



Kinds of wood	Elements on boat
Oak	Beam, keel, frame and board
Elm	Beam, keel, frame and stem
Fir	Beam, cabin and mast
Mahogany	Everywhere on boat
White Pine	Board, deck
Nordic Pine	Mast
Yellow Pine	Mast
Teak	Deck

Table 3.1. Woods used in construction. (Kahraman 2000)

3.5. Composite Materials

Composite materials are formed by combining two or more materials that have quite different properties. The different materials work together to give the composite unique properties.

Most composites are made up of just two materials. One material, which is called **matrix** or **binder**, surrounds and binds together a cluster of fibers or fragments of a much stronger material, which is the **reinforcement**.

Humans have been using composite materials for thousands of years. The first known application of composite materials occurred several thousand years ago when the Egyptians started using straw strengthened sun dried clay bricks in construction. Since that time great strides have been made in the development of composite materials. They now offer the promise of new products with extraordinary strength, stiffness, chemical and temperature resistance.

Market	1997 (Millions)	1998 (Millions)	1997-1998 Change	1999 (Millions)	1998-1999 Change
Transportation	$1,095.2	$1,139.0	+4.0%	$1,196.6	+5.0%
Construction	$689.6	$740.0	+7.3%	$781.1	+4.2%
Corrosion Resistant Equipment	$396.0	$423.9	+7.0%	$435.1	+2.6%
Marine	$353.3	$364.0	+3.0%	$377.5	+3.7%
Electrical/Electronic	$348.2	$360.3	+3.4%	$376.6	+4.5%
Consumer & Recreation	$210.0	$225.3	+7.3%	$235.2	+4.4%
Appliance Business Equipment	$185.0	$197.7	+6.9%	$206.8	+4.6%
Aircraft/Aerospace/Defense	$23.9	$22.7	-5.0%	$23.8	+5.0%
Other	$110.8	$117.0	+6.0%	$122.3	+4.5%
Total	**$3,412.0**	**$3,589.9**	**+5.2%**	**$3,755.0**	**+4.6%**

Table 3.2. U.S. FRP Composites Shipments by Market Segment (EPRI 2000)

Composites have been used to build boats since the 1950s and now dominate the boatbuilding world. They have generally been used to replace traditional materials such as wood, aluminum and steel. Significant advantages over these traditional materials include higher strength, lighter weight, greater corrosion resistance, dimensional stability, higher dielectric strength, and improved design flexibility. (EPRI 2000)

Reinforcements for marine composite structures are primarily E-glass due to its cost for strength and workability characteristics. In contrast, the aerospace industry use carbon fiber. In general, carbon, aramid fibers and other specialty reinforcements are used in the marine field where structures are highly engineered for optimum efficiency.

Materials form an integral part of the way composite structures perform. Because creating a structural material from diverse constituent compounds, material science concepts are essential to the understanding of how structural composites behave. Composite materials can be divided to three main part:

- Reinforcements;
- Resins; and
- Core Materials.

3.5.1. Reinforcement Materials

The role of the reinforcement in a composite material is fundamentally one of increasing the mechanical properties of the neat resin system.

All of the different fibers used in composites have different properties and so affect the properties of the composite in different ways. However, individual fibers or fiber bundles can only be used on their own in a few processes such as filament winding. For most other applications, the fibers need to be arranged into some form of sheet, known as a fabric, to make handling possible. Different ways for assembling fibers into sheets and the variety of fiber orientations possible lead to there being many different types of fabrics, each of which has its own characteristics.

Glass fibers: 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.

By blending quarry products (sand, kaolin, limestone, colemanite) at 1,600C, liquid glass is formed. The liquid is passed through micro-fine bushings and simultaneously cooled to produce glass fiber filaments. WEB_17 (2004)

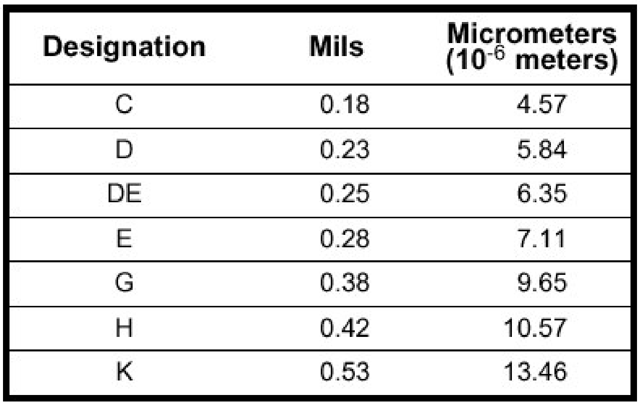
The filaments are drawn together into a strand or roving and coated with a "size" to provide filament cohesion and protect the glass from abrasion. By variation of the "recipe", different types of glass can be produced. The types used for structural reinforcements are as follows:

a. E-glass (electrical) - lower alkali content and stronger than A glass (alkali). Good tensile and compressive strength and stiffness, good electrical properties and relatively low cost, but impact resistance relatively poor.

b. C-glass (chemical) - best resistance to chemical attack. Mainly used in the form of surface tissue in the outer layer of laminates used in chemical and water pipes and tanks.

c. R, S or T-glass – manufacturers trade names for equivalent fibers having higher tensile strength and modulus than E glass, with better wet strength retention. Developed for aerospace and defense industries, and used in some hard ballistic armour applications.

The excellent tensile strength of glass fibers, however, may deteriorate when loads are applied for long periods of time. Continuous glass fibers are formed by extruding molten glass to filament diameters between 5 and 25 micrometers. Table 3.3 depicts the designations of fiber diameters commonly used in the FRP industry.



Designation	Mils	Micrometers (10^{-6} meters)
C	0.18	4.57
D	0.23	5.84
DE	0.25	6.35
E	0.28	7.11
G	0.38	9.65
H	0.42	10.57
K	0.53	13.46

Table 3.3. Glass Fiber Diameter Designations (Greene 2004)

Polymer Fibers: The most common aramid fiber is Kevlar ® developed by DuPont. This is the predominant organic reinforcing fiber, whose use dates to the early 1970s as a replacement for steel belting in tires. The outstanding features of aramids are low weight, high tensile strength and modulus, impact and fatigue resistance, and weaveability. Compressive performance of aramids is not as good as glass, as they show nonlinear ductile behavior at low strain values. Water absorption of un-impregnated Kevlar ® 49 is greater than other reinforcements, although ultra-high modulus Kevlar ® 149 absorbs almost two thirds less than Kevlar ® 49. The unique characteristics of aramids can best be exploited if appropriate weave style and handling techniques are used.

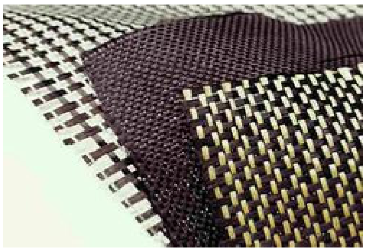
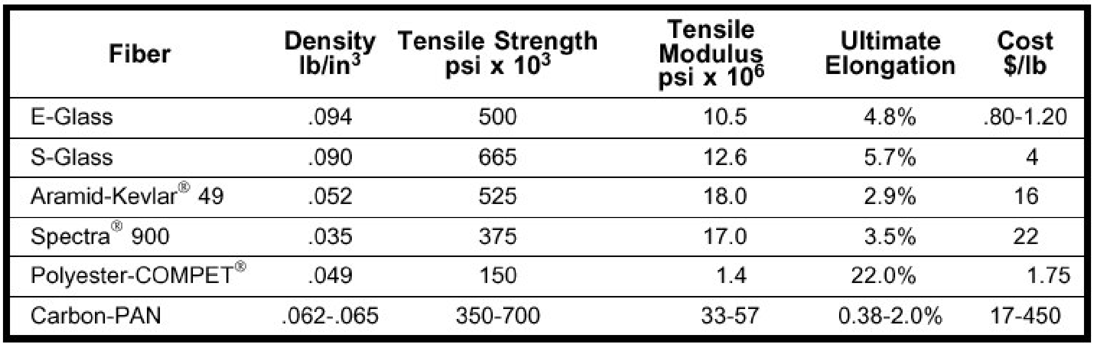


Figure 3.1. Carbon fiber. WEB_9 (2004)

Allied Corporation developed a high strength/modulus extended chain polyethylene fiber called Spectra ® that was introduced in 1985. Room temperature specific mechanical properties of Spectra ® are slightly better than Kevlar ® , although performance at elevated temperatures falls off. Chemical and wear resistance data is superior to the aramids.



Fiber	Density lb/in^3	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^6	Ultimate Elongation	Cost $/lb
E-Glass	.094	500	10.5	4.8%	.80-1.20
S-Glass	.090	665	12.6	5.7%	4
Aramid-Kevlar® 49	.052	525	18.0	2.9%	16
Spectra® 900	.035	375	17.0	3.5%	22
Polyester-COMPET®	.049	150	1.4	22.0%	1.75
Carbon-PAN	.062-.065	350-700	33-57	0.38-2.0%	17-450

Table 3.4. Mechanical Properties of Reinforcement Fibers (Greene 2004)

Polyester and nylon thermoplastic fibers have recently been introduced to the marine industry as primary reinforcements and in a hybrid arrangement with fiberglass. Allied Corporation has developed a fiber called COMPET ® , which is the product of applying a finish to PET fibers that enhances matrix adhesion properties. Hoechst-Celanese manufactures a product called Treveria ® , which is a heat treated polyester fiber fabric designed as a "bulking" material and as a gel coat barrier to reduce "print-through." Although polyester fibers have fairly high strengths, their stiffness is considerably below that of glass. Other attractive features include low density, reasonable cost, good impact and fatigue resistance, and potential for vibration damping and blister resistance.

Carbon Fibers: The terms "carbon" and "graphite" fibers are typically used interchangeably, although graphite technically refers to fibers that are greater than 99% carbon composition versus 93 to 95% for PAN-base fibers. All continuous carbon fibers produced to date are made from organic precursors, which in addition to PAN (polyacrylonitrile), include rayon and pitches, with the latter two generally used for low modulus fibers.

Carbon fibers offer the highest strength and stiffness of all commonly used reinforcement fibers. The fibers are not subject to stress rupture or stress corrosion, as with glass and aramids. High temperature performance is particularly outstanding. The major drawback to he PAN-base fibers is their relative cost, which is a function of high precursor costs and an energy intensive manufacturing process. Table 3.4 shows some comparative fiber performance data.

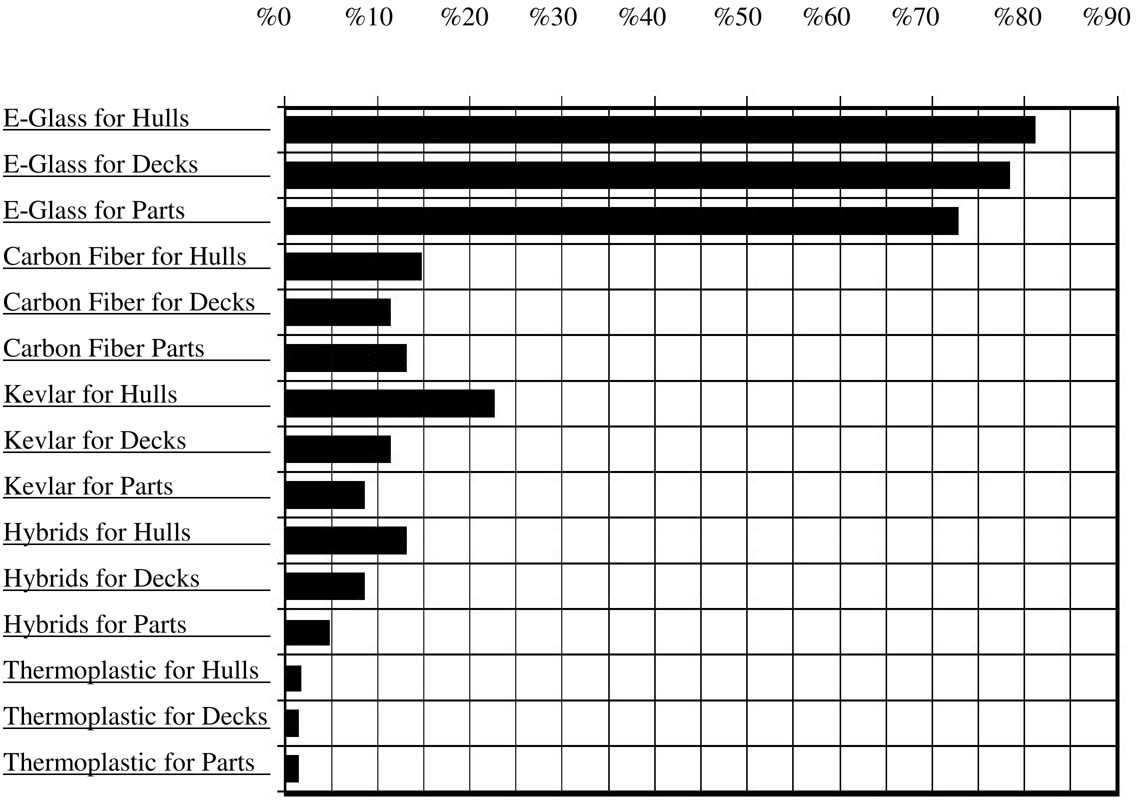


Figure 3.2. Marine Industry Reinforcement Material Use (Greene 2004)

Hybrid Fabrics: The term hybrid refers to a fabric that has more than one type of structural fiber in its construction. In a multi-layer laminate if the properties of more than one type of fiber are required, then it would be possible to provide this with two fabrics, each containing the fiber type needed. However, if low weight or extremely thin laminates are required, a hybrid fabric will allow the two fibers to be presented in just one layer of fabric instead of two. It would be possible in a woven hybrid to have one fiber running in the weft direction and the second fiber running in the warp direction, but it is more common to find alternating threads of each fiber in each warp/weft direction. Al-though hybrids are most commonly found in 0/90 woven fabrics, the principle is also used in 0/90 stitched, unidirectional and multiaxial fabrics. The most usual hybrid combinations are:

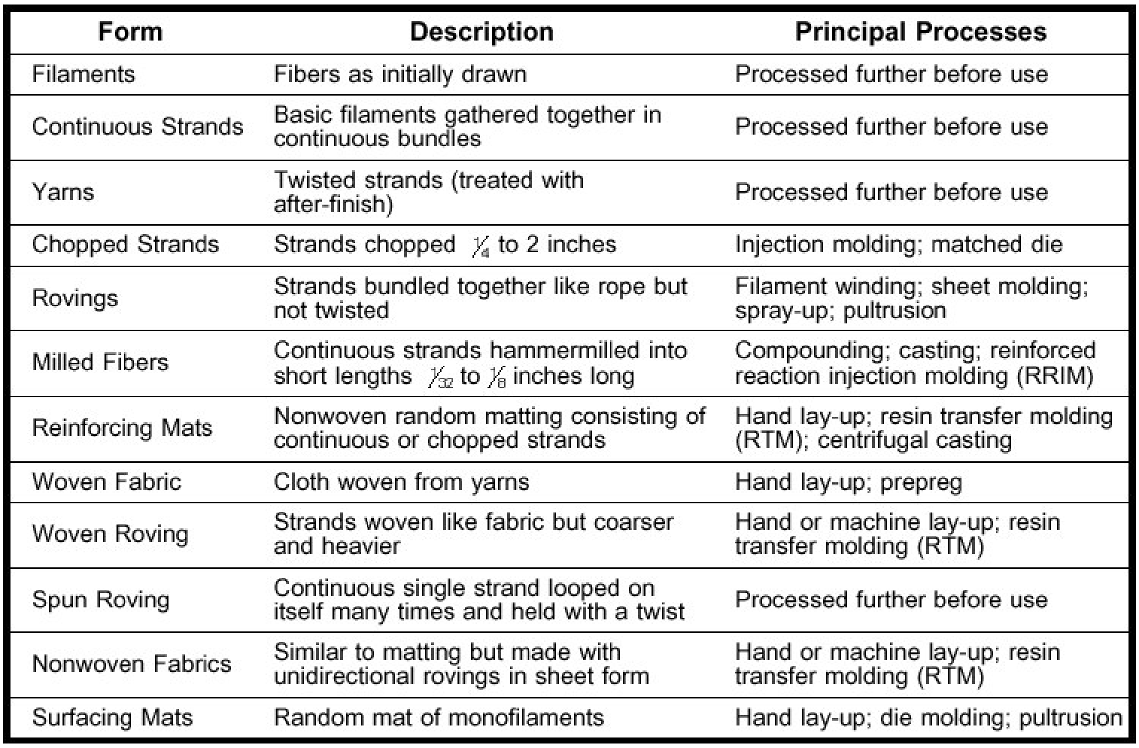
Carbon / Aramid - The high impact resistance and tensile strength of the aramid fiber combines with high the compressive and tensile strength of carbon. Both fibers have low density but relatively high cost.

Aramid / Glass - The low density, high impact resistance and tensile strength of aramid fiber combines with the good compressive and tensile strength of glass, coupled with its lower cost.

Carbon / Glass - Carbon fiber contributes high tensile compressive strength and stiffness and reduces the density, while glass reduces the cost.

3.5.2. Reinforcement Construction

Reinforcement materials are combined with resin systems in a variety of forms to create structural laminates. The percent of manufacturers using various reinforcement styles is represented in Figure 3.5. Table 3.5 provides definitions for the various forms of reinforcement materials. Some of the lower strength non-continuous configurations are limited to fiberglass due to processing and economic considerations.



Form	Description	Principal Processes
Filaments	Fibers as initially drawn	Processed further before use
Continuous Strands	Basic filaments gathered together in continuous bundles	Processed further before use
Yarns	Twisted strands (treated with after-finish)	Processed further before use
Chopped Strands	Strands chopped 1/4 to 2 inches	Injection molding; matched die
Rovings	Strands bundled together like rope but not twisted	Filament winding; sheet molding; spray-up; pultrusion
Milled Fibers	Continuous strands hammermilled into short lengths 1/32 to 1/8 inches long	Compounding; casting; reinforced reaction injection molding (RRIM)
Reinforcing Mats	Nonwoven random matting consisting of continuous or chopped strands	Hand lay-up; resin transfer molding (RTM); centrifugal casting
Woven Fabric	Cloth woven from yarns	Hand lay-up; prepreg
Woven Roving	Strands woven like fabric but coarser and heavier	Hand or machine lay-up; resin transfer molding (RTM)
Spun Roving	Continuous single strand looped on itself many times and held with a twist	Processed further before use
Nonwoven Fabrics	Similar to matting but made with unidirectional rovings in sheet form	Hand or machine lay-up; resin transfer molding (RTM)
Surfacing Mats	Random mat of monofilaments	Hand lay-up; die molding; pultrusion

Table 3.5. Description of Various Forms of Reinforcements (Greene 2004)

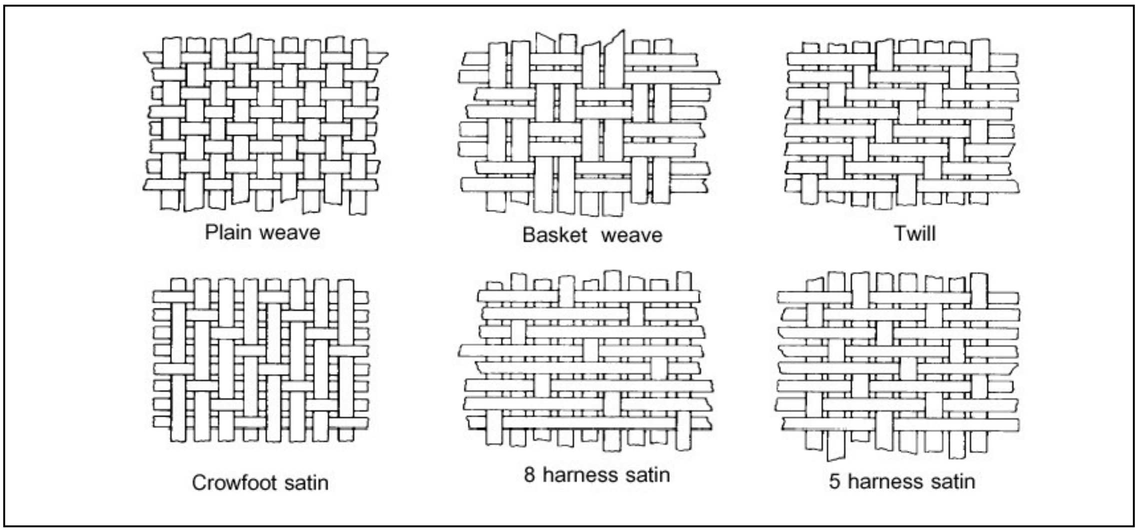


Figure 3.3. Reinforcement Fabric Construction Variations (Greene 2004)

Wovens: Woven composite reinforcements generally fall into the category of cloth or woven roving. Their use in marine construction is limited to small parts and repairs. Particular weave patterns include plain weave, which is the most highly interlaced; basket weave, which has warp and fill yarns that are paired up; and satin weaves, which exhibit a minimum of interlacing. The satin weaves are produced in standard four-, five- or eight-harness configurations, which exhibit a corresponding increase in resistance to shear distortion (easily draped). Figure 3.3 shows some commercially available weave patterns.

Woven roving reinforcements consist of flattened bundles of continuous strands in a plain weave pattern with slightly more material in the warp direction. This is the most common type of reinforcement used for large marine structures because it is available in fairly heavy weights (24 ounces per square yard is the most common), which enable a rapid build up of thickness. Also, directional strength characteristics are possible with a material that is still fairly drapable. Impact resistance is enhanced because the fibers are continuously woven.

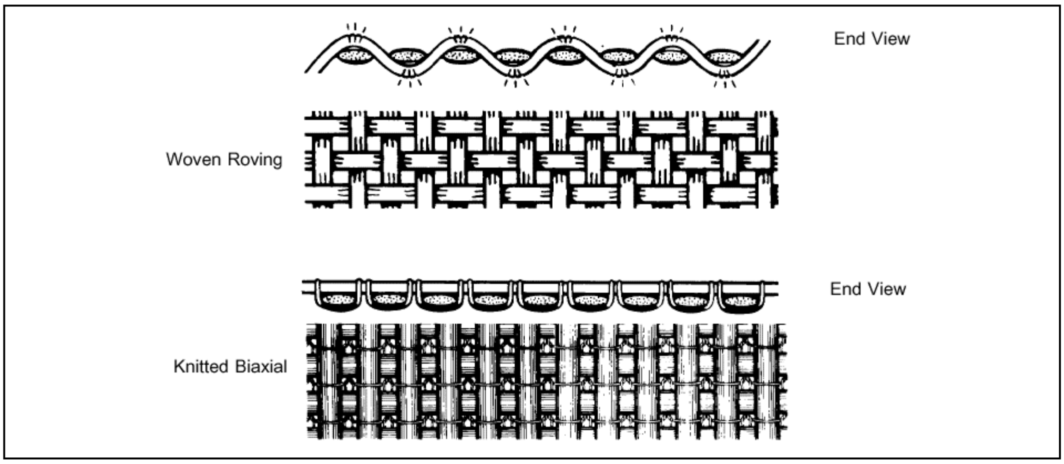


Figure 3.4. Comparison of Conventional Woven Roving and a Knitted Biaxial Fabric Showing Theoretical Kink Stress in Woven Roving (Greene 2004)

Knits: Knitted reinforcement fabrics were first introduced by Knytex ® in 1975 to provide greater strength and stiffness per unit thickness as compared to woven rovings. A knitted reinforcement is constructed using a combination of unidirectional reinforcements that are stitched together with a nonstructural synthetic such as polyester. A layer of mat may also be incorporated into the construction. The process provides the advantage of having the reinforcing fiber lying flat versus the crimped orientation of woven roving fiber. Additionally, reinforcements can be oriented along any combination of axes. Superior glass to resin ratios are also achieved, which makes overall laminate costs competitive with traditional materials. Figure 3.4 shows a comparison of woven roving and knitted construction.

Omnidirectional: Omnidirectional reinforcements can be applied during hand lay-up as prefabricated mat or via the spray-up process as chopped strand mat. Chopped strand mat consists of randomly oriented glass fiber strands that are held together with a soluble resinous binder. Continuous strand mat is similar to chopped strand mat, except that the fiber is continuous and laid down in a swirl pattern. Both hand lay-up and spray-up methods produce plies with equal properties along the x and y-axes and good interlaminar shear strength. This is a very economical way to build up thickness, especially with complex molds. Mechanical properties are less than other reinforcements.

Unidirectional: Pure unidirectional construction implies no structural reinforcement in the fill direction. Ultra high strength/modulus material, such as carbon fiber, is sometimes used in this form due to its high cost and specificity of application. Material widths are generally limited due to the difficulty of handling and wet-out. Anchor Reinforcements has recently introduced a line of unidirectional that are held together with a thermoplastic web binder that is compatible with thermoset resin systems. The company claims that the material is easier to handle and cut than traditional pure unidirectional material. Typical applications for unidirectionals include stem and centerline stiffening as well as the tops of stiffeners. Entire hulls are fabricated from unidirectional reinforcements when an ultra high performance laminate is desired.

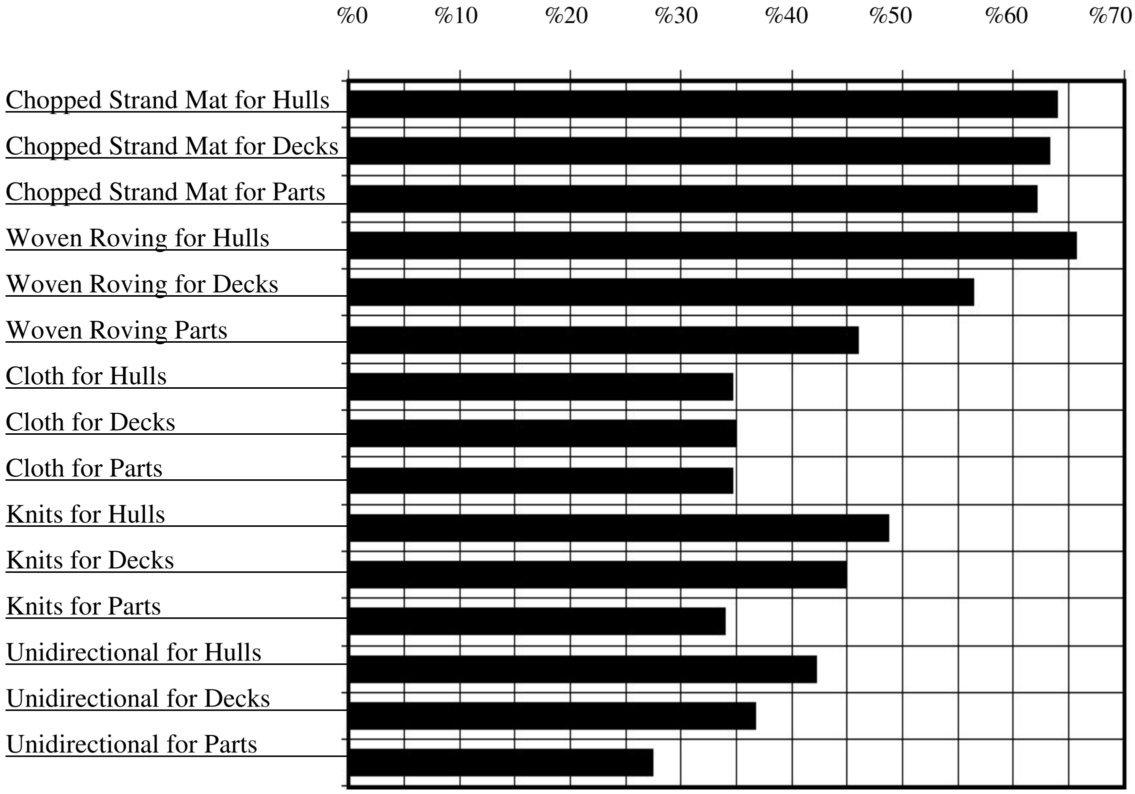


Figure 3.5. Marine Industry Reinforcement Style Use (Greene 2004)

3.5.3. Resins

For the matrix, many modern composites use thermosetting or thermosoftening plastics. The plastics are polymers that hold the reinforcement together and help to determine the physical properties of the end product. The percent of manufacturers using various resin systems is represented in Figure 3.6.

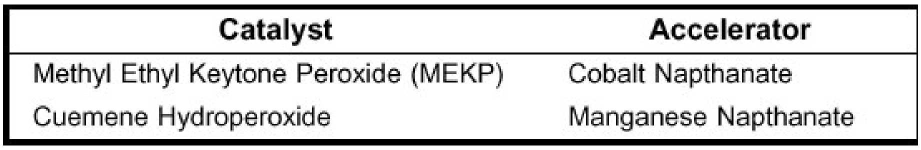
Polyester: Polyester resins are the most widely used resin systems, particularly in the marine industry. By far the majority of dinghies, yachts and workboats built in composites make use of this resin system.

Polyester resins are the simplest, most economical resin systems that are easiest to use and show good chemical resistance.

Most polyesters are air inhibited and will not cure when exposed to air. Typically, paraffin is added to the resin formulation, which has the effect of sealing the surface during the cure process. However, the wax film on the surface presents a problem for secondary bonding or finishing and must be physically removed. Non-air inhibited resins do not present this problem and are therefore, more widely accepted in the marine industry.

The two basic polyester resins used in the marine industry are orthophthalic and isophthalic. The ortho resins were the original group of polyesters developed and are still in widespread use. They have somewhat limited thermal stability, chemical resistance, and processability characteristics. The iso resins generally have better mechanical properties and show better chemical resistance. Their increased resistance to water permeation has prompted many builders to use this resin as a gel coat or barrier coat in marine laminates.

Curing of polyester without the addition of heat is accomplished by adding accelerator along with the catalyst. Gel times can be carefully controlled by modifying formulations to match ambient temperature conditions and laminate thickness.The following combinations of curing additives are most common for use with polyesters:

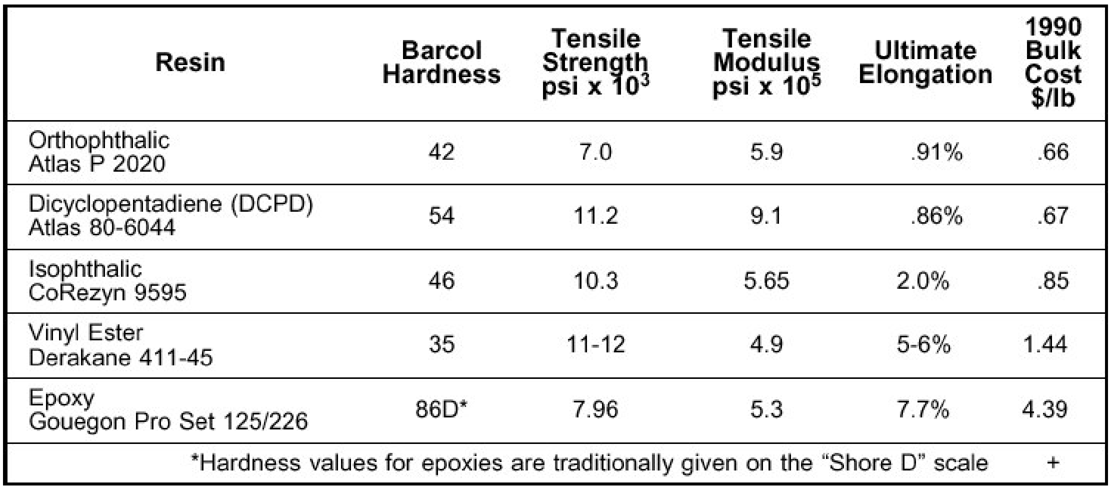


Catalyst	Accelerator
Methyl Ethyl Keytone Peroxide (MEKP)	Cobalt Napthanate
Cuemene Hydroperoxide	Manganese Napthanate

Table 3.6. Polyester Resin Catalyst and Accelerator Combinations (Scott 1996)

Other resin additives can modify the viscosity of the resin if vertical or overhead surfaces are being laminated. This effect is achieved through the addition of silicon dioxide, in which case the resin is called thixotropic. Various other fillers are used to reduce resin shrinkage upon cure, a useful feature for gel coats.

Vinyl Ester: Vinyl ester resins are unsaturated resins prepared by the reaction of a monofunctional unsaturated acid, such as methacrylic or acrylic, with a bisphenol diepoxide. The resulting polymer is mixed with an unsaturated monomer, such as styrene. The handling and performance characteristics of vinyl esters are similar to polyesters. Some advantages of the vinyl esters, which may justify their higher cost, include superior corrosion resistance, hydrolytic stability, and excellent physical properties, such as impact and fatigue resistance. It has been shown that a 20 to 60 mil layer with a vinyl ester resin matrix can provide an excellent permeation barrier to resist blistering in marine laminates.



Resin	Barcol Hardness	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^5	Ultimate Elongation	1990 Bulk Cost $/lb
Orthophthalic Atlas P 2020	42	7.0	5.9	.91%	.66
Dicyclopentadiene (DCPD) Atlas 80-6044	54	11.2	9.1	.86%	.67
Isophthalic CoRezyn 9595	46	10.3	5.65	2.0%	.85
Vinyl Ester Derakane 411-45	35	11-12	4.9	5-6%	1.44
Epoxy Gouegon Pro Set 125/226	86D*	7.96	5.3	7.7%	4.39
*Hardness values for epoxies are traditionally given on the “Shore D” scale					+

Table 3.7. Comparative Data for Some Thermoset Resin Systems (Greene 2004)

Epoxy: Epoxy resins are a broad family of materials that contain a reactive functional group in their molecular structure. Epoxy resins show the best performance characteristics of all the resins used in the marine industry. Aerospace applications use epoxy almost exclusively, except when high temperature performance is critical. The high cost of epoxies and handling difficulties have limited their use for large marine structures. Table 3.7. shows some comparative data for various thermoset resin systems.

Thermoplastics: Thermoplastics have one- or two-dimensional molecular structures, as opposed to three-dimensional structures for thermosets. The thermoplastics generally come in the form of molding compounds that soften at high temperatures. Polyethylene, polystyrene, polypropylene, polyamides and nylon are examples of thermoplastics. Their use in the marine industry has generally been limited to small boats and recreational items. Reinforced thermoplastic materials have recently been investigated for the large scale production of structural components. Some attractive features include no exotherm upon cure, which has plagued filament winding of extremely thick sections with thermosets, and enhanced damage tolerance. Processability and strengths compatible with reinforcement material are key areas currently under development.

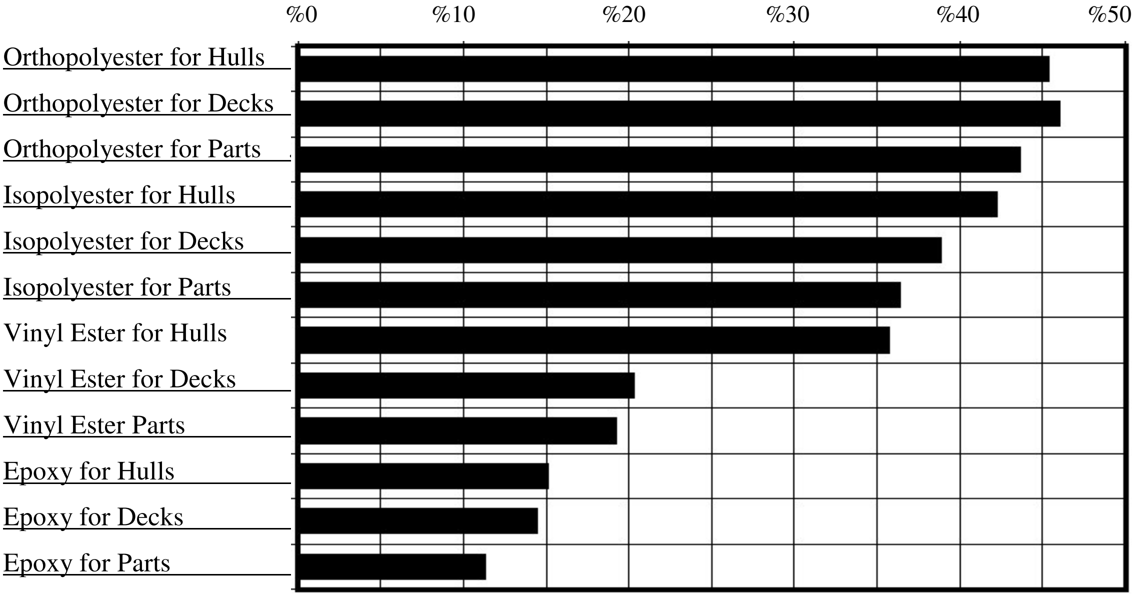


Figure 3.6. Marine Industry Resin System Use (Greene 2004)

3.5.4. Core Materials

The purpose of a core in a composite laminate is to increase the laminate's stiffness by effectively 'thickening' it with a low-density core material. This can provide a dramatic increase in stiffness for very little additional weight.

Balsa: The most commonly used wood core is end-grain balsa. Balsa wood cores first appeared in the 1940's in flying boat hulls, which were aluminium skinned and balsa-cored to withstand the repeated impact of landing on water. This performance led the marine industry to begin using end-grain balsa as a core material in FRP construction. Apart from its high compressive properties, its advantages include being a good thermal insulator offering good acoustic absorption.

The material will not deform when heated and acts as an insulating and ablative layer in a fire, with the core charring slowly, allowing the non-exposed skin to remain structurally sound. It also offers positive flotation and is easily worked with simple tools and equipment. Balsa core is available as contoured end-grain sheets 3 to 50mm thick on a backing fabric, and rigid end-grain sheets up to 100mm thick. These sheets can be provided ready resin-coated for vacuum-bagging, prepreg or pressure-based manufacturing processes such as RTM. One of the disadvantages of balsa is its high minimum density, with 100kg/m3 being a typical minimum.

This problem is exacerbated by the fact that balsa can absorb large quantities of resin during lamination, although pre-sealing the foam can reduce this. Its use is therefore normally restricted to projects where optimum weight saving is not required or in locally highly stressed areas.

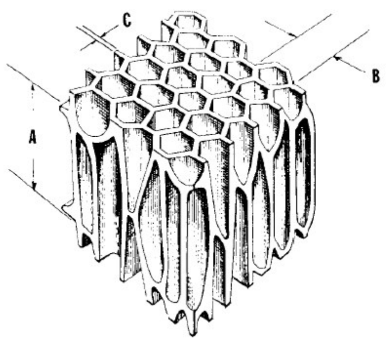


Figure 3.7. Balsa Cell Geometry with A =Average Cell Length = .025"; B = Average Cell Diameter = .00126"; C = Average CellWall Thickness = .00006". WEB_3 (2004)

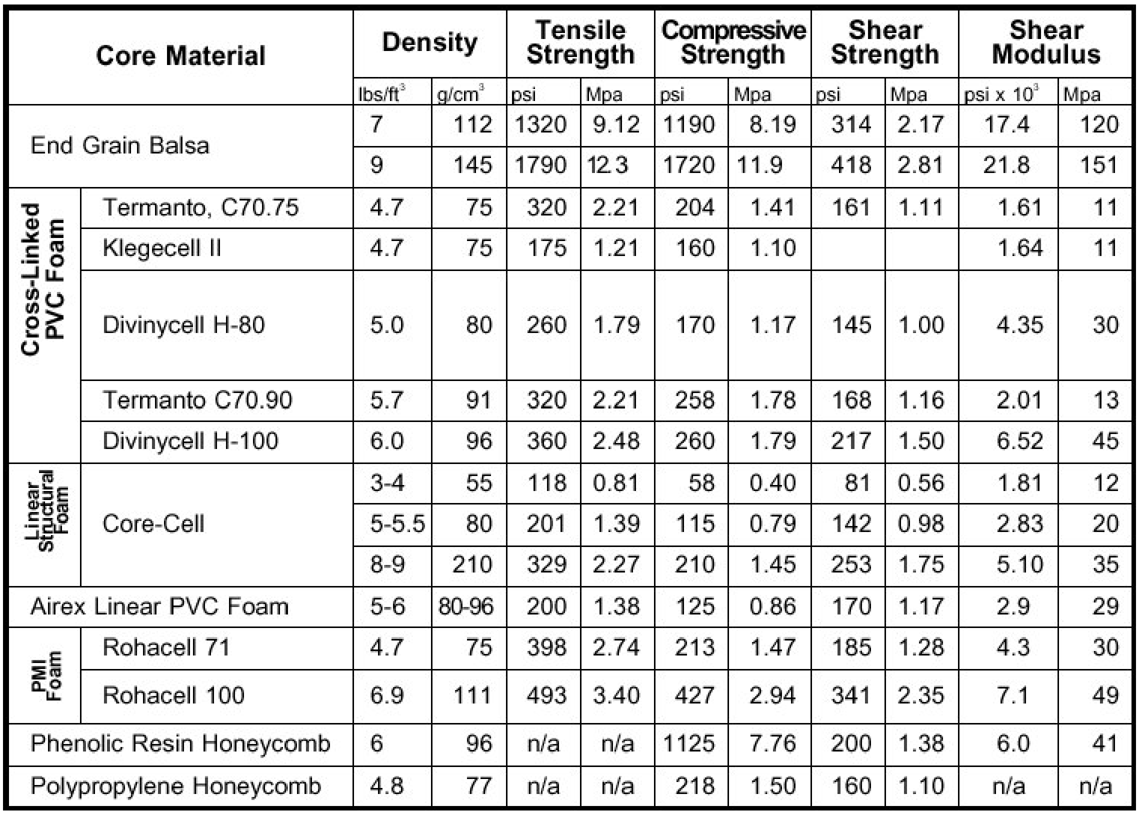
Thermoset Foams: Foamed plastics such as cellular cellulose acetate (CCA), polystyrene, and polyurethane are very light (about 2 lbs/ft 3) and resist water, fungi and decay. These materials have very low mechanical properties and polystyrene will be attacked by polyester resin. These foams will not conform to complex curves. Use is generally limited to buoyancy rather than structural applications. Polyurethane is often foamed in-place when used as a buoyancy material.

Syntactic Foams: Syntactic foams are made by mixing hollow microspheres of glass, epoxy and phenolic into fluid resin with additives and curing agents to form a moldable, curable, lightweight fluid mass. Omega Chemical has introduced a sprayable syntactic core material called SprayCore TM . The company claims that thicknesses of 3/8" can be achieved at densities between 30 and 43 lbs/ft 3 . The system is being marketed as a replacement for core fabrics with superior physical properties.

Cross Linked PVC Foams: Polyvinyl foam cores are manufactured by combining a polyvinyl copolymer with stabilizers, plasticizers, cross-linking compounds and blowing agents. The mixture is heated under pressure to initiate the cross-linking reaction and then submerged in hot water tanks to expand to the desired density. The resulting material is thermoplastic, enabling the material to conform to compound curves of a hull. PVC foams have almost exclusively replaced urethane foams as a structural core material, except in configurations where the foam is “blown” in place. A number of manufacturers market cross-linked PVC products to the marine industry in sheet form with densities ranging from 2 to 12 pounds per ft 3.

Linear PVC Foam: Airex ® and Core-Cell ® are examples of linear PVC foam core produced for the marine industry. Unique mechanical properties are a result of a non-connected molecular structure, which allows significant displacements before failure. In comparison to the cross linked (non-linear) PVCs, static properties will be less favorable and impact will be better.

Honeycomb: Various types of manufactured honeycomb cores are used extensively in the aerospace industry. Constituent materials include aluminum, phenolic resin impregnated fiberglass, polypropylene and aramid fiber phenolic treated paper. Although the fabrication of extremely lightweight panels is possible with honeycomb cores, applications in a marine environment are limited due to the difficulty of bonding to complex face geometries and the potential for significant water absorption. The Navy has had some corrosion problems when an aluminum honeycomb core was used for ASROC housings. Data on a Nomex ® phenolic resin honeycomb product is presented in Table 3.8. (Greene 2004)



Core Material		Density		Tensile Strength		Compressive Strength		Shear Strength		Shear Modulus	
		lbs/ft^3	g/cm^3	psi	Mpa	psi	Mpa	psi	Mpa	psi x 10^3	Mpa
End Grain Balsa		7	112	1320	9.12	1190	8.19	314	2.17	17.4	120
		9	145	1790	12.3	1720	11.9	418	2.81	21.8	151
Cross-Linked PVC Foam	Termanto, C70.75	4.7	75	320	2.21	204	1.41	161	1.11	1.61	11
	Klegecell II	4.7	75	175	1.21	160	1.10			1.64	11
	Divinycell H-80	5.0	80	260	1.79	170	1.17	145	1.00	4.35	30
	Termanto C70.90	5.7	91	320	2.21	258	1.78	168	1.16	2.01	13
	Divinycell H-100	6.0	96	360	2.48	260	1.79	217	1.50	6.52	45
Linear Structural Foam	Core-Cell	3-4	55	118	0.81	58	0.40	81	0.56	1.81	12
		5-5.5	80	201	1.39	115	0.79	142	0.98	2.83	20
		8-9	210	329	2.27	210	1.45	253	1.75	5.10	35
Airex Linear PVC Foam		5-6	80-96	200	1.38	125	0.86	170	1.17	2.9	29
PMI Foam	Rohacell 71	4.7	75	398	2.74	213	1.47	185	1.28	4.3	30
	Rohacell 100	6.9	111	493	3.40	427	2.94	341	2.35	7.1	49
Phenolic Resin Honeycomb		6	96	n/a	n/a	1125	7.76	200	1.38	6.0	41
Polypropylene Honeycomb		4.8	77	n/a	n/a	218	1.50	160	1.10	n/a	n/a

Table 3.8. Comparative Data for Some Sandwich Core Materials (Greene 2004)

PMI Foam: Rohm Tech, Inc. markets a polymrthacrylimide (PMI) foam for composite construction called Rohacell ® . The material requires minimum laminating pressures to develop good peel strength. The most attractive feature of this material is its ability to withstand curing temperatures in excess of 350°F, which makes it attractive for use with prepreg reinforcements. Table 3.8 summarizes the physical properties of a common grade of Rohacell ® .

FRP Planking: Seemann Fiberglass, Inc. developed a product called C-Flex ® in 1973 to help amateurs build a cost effective one-off hull. The **planking** consists of rigid fiberglass rods held together with unsaturated strands of continuous fiberglass rovings and a light fiberglass cloth. The self-supporting material will conform to compound curves. Typical application involves a set of male frames as a form. The planking has more rigidity than PVC foam sheets, which eliminates the need for extensive longitudinal stringers on the male mold.

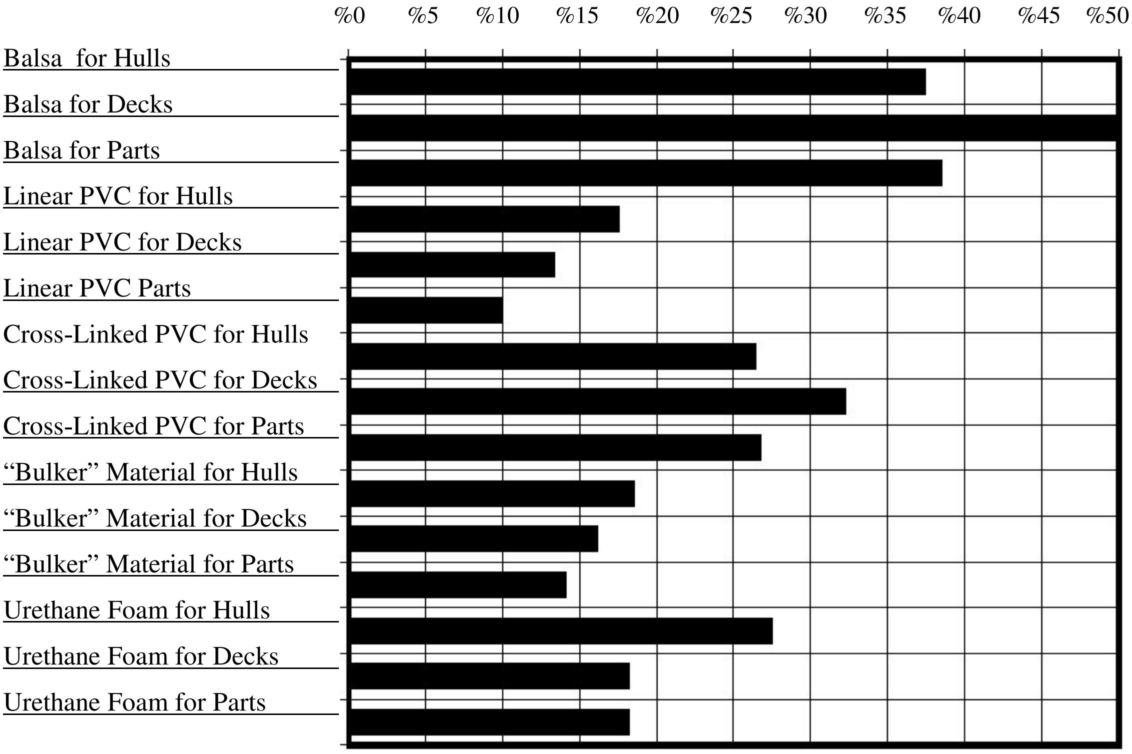


Figure 3.8. Marine Industry Core Material Use (Greene 2004)

Core Fabrics: Various natural and synthetic materials are used to manufacture products to build up laminate thickness economically. One such product that is popular in the marine industry is Firet Coremat, a spun-bound polyester produced by Lantor. Hoechst Celanese has recently introduced a product called Trevira , which is a continuous filament polyester. The continuous fibers seem to produce a fabric with superior mechanical properties. Ozite produces a core fabric called Compozitex TM from inorganic vitreous fibers. The manufacturer claims that a unique manufacturing process creates a mechanical fiber lock within the fabric. Although many manufacturers have had much success with such materials in the center of the laminate, the use of a Nonstructural thick ply near the laminate surface to eliminate print-through requires engineering forethought. The high modulus, low strength ply can produce premature cosmetic failures. Other manufacturers have started to produce “bulking” products that are primarily used to build up laminate thickness.

Plywood: Plywood should also be mentioned as a structural core material, although fiberglass is generally viewed as merely sheathing when used in conjunction with plywood. Exceptions to this characterization include local reinforcements in way of hardware installations where plywood replaces a lighter density core to improve compression properties of the laminate. Plywood is also sometimes used as a form for longitudinals, especially in way of engine mounts. Concern over the continued propensity for wood to absorb moisture in a maritime environment, which can cause swelling and subsequent delamination, has precipitated a decline in the use of wood in conjunction with FRP. The uneven surface of plywood can make it a poor bonding surface. Also, the low strength and low strain characteristics of plywood can lead to premature failures when used as a core with thin skins. The technique of laminating numerous thin plies of wood developed by the Gougeon Brothers and known as wood epoxy saturation technique (WEST ® System) eliminates many of the shortcomings involved with using wood in composite structures. (Greene 2004)

3.6. Comparison of the Materials used in Boat Construction

The most important thing for boat design and production is to determine the material, which have the different advantage and options for designer.

The intended use of the vessel affects the material choice because that will set the performance expected, the level of maltreatment to which it will be subjected, the standard of finish required and the amount of maintenance, which is acceptable. A boat intended for commercial fishing or cargo work will have very different needs from one, which is to compete in the high-class charter fleets.

In the size range, 10m to 30m,the principal materials are wood, steel, fiber-reinforced plastic (FRP), ferrocement and aluminum.

In this range, wood is in general lighter than steel, but because of the greater thickness of the hull construction, requires a larger hull for the same internal capacity.

Ferro cement will in general be heavier than steel if near equivalent strengths are to be obtained. Although there can be a slight reduction in size for equivalent internal capacity, the increased weight should be allowed for in the design calculation. Care must be taken in weight control and the economic consequences of increased weight balanced against such factors as lower initial cost and reduced maintenance.

Aluminum construction is the highest in first cost of the materials being considered for boats but this initial cost can be offset by potential savings in operational costs and maintenance over the lifetime of the vessel.

FRP is the most common material in modern boatbuilding. Properly done, it produces sound boats capable of safely travelling to almost any corner of the world. When a mould is available for the chosen design, the hull, deck and available modules can be produced with a minimum of effort and in a very short time.

3.6.1. Comparison of mechanical characteristics

To get a correct insight into the qualities of various materials; tensile strength, bending strength and rigidity must be investigated separately.

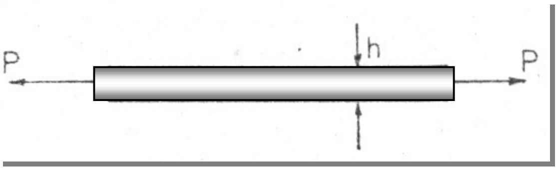


Figure 3.9. Beam submitted to tensile force P (Verweij 1978)

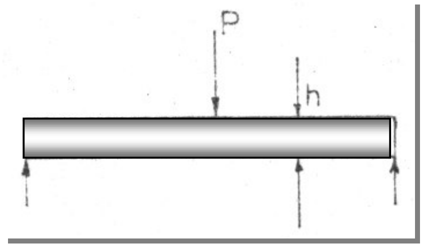


Figure 3.10. Beam submitted to bending force P (Verweij 1978)

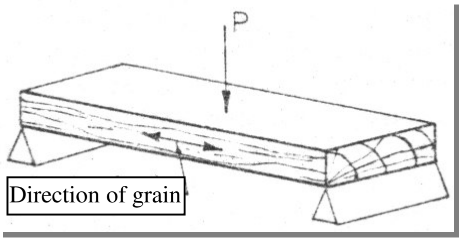


Figure 3.11. Wooden plate supported at right angle to grain.(Verweij 1978)

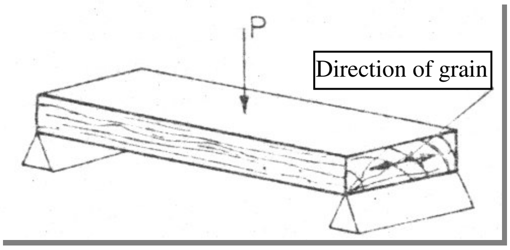


Figure 3.12. Wooden plate supported at parallel to grain. (Verweij 1978)

- **Criterion for tensile strength**

If a beam in figure 3.9. with unit width and thickness **H** is now subjected to tensile force $\mathbf{Ft}$, then the tensile stress $\boldsymbol{\sigma t}$ equals $\mathbf{Ft/\ H}$. Beams of different materials are of equal weight of their thickness, **H**, varies in inverse ratio to their specific gravity. Therefore, the maximum tensile force which beams of equal weight but of different materials can withstand is dependent on the ratio: $\boldsymbol{\sigma t / \gamma}$

- **Criterion for bending strength**

The beam in figure 3.10 with unit width and thickness **H** is now subjected to a bending force **Fb**. This results in a bending stress:

σ b =M ; M= ¼ Fbl = bending moment

W= 1/6 H^2 = modulus of section

The maximum bending force which beam of equal weight can withstand is dependent on the ratio: **$\sigma b / \gamma^2$**

- **Criterion for rigidity**

Apart from strength, we must consider stiffness. It may happen that a beam (figure 3.10.) bends so much under a force Fb that the deflection, a, surpasses acceptable values, although the bending stress σb may stay within normal limits. Therefore, stiffness and strength must be dealt with separately. The deflection, a, depends on the ratio Fb/ EI where E= modulus elasticity, and I= moment of inertia= 1/12 . h^3

The bending force which causes beams of equal weight to deflect equally depends on the ratio: **E/ γ^3**

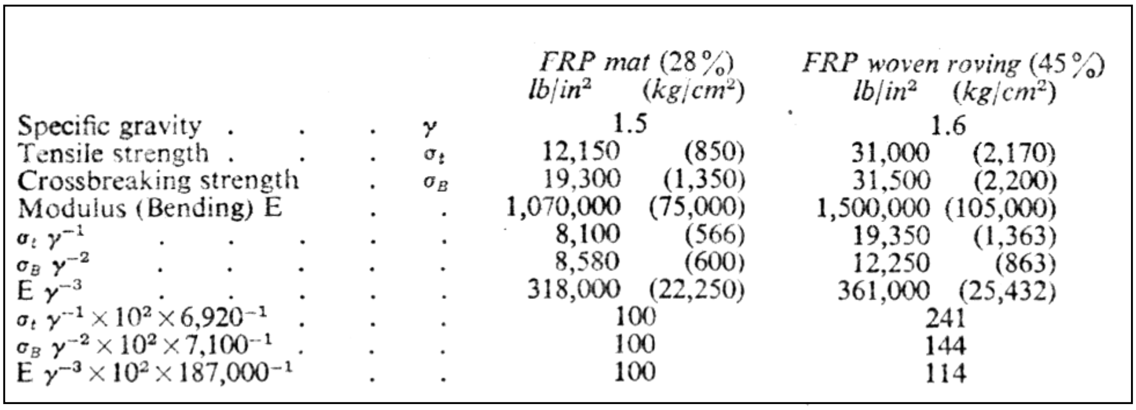
- **Summary of criterion**

For a given weight:
Tensile strength proportional to: **$\sigma t / \gamma$**
Bending strength proportional to: **$\sigma t / \gamma^2$**
Rigidity proportional to: **E / γ^3**

1. Comparison of FRP with steel and light alloy as regards strength and rigidity

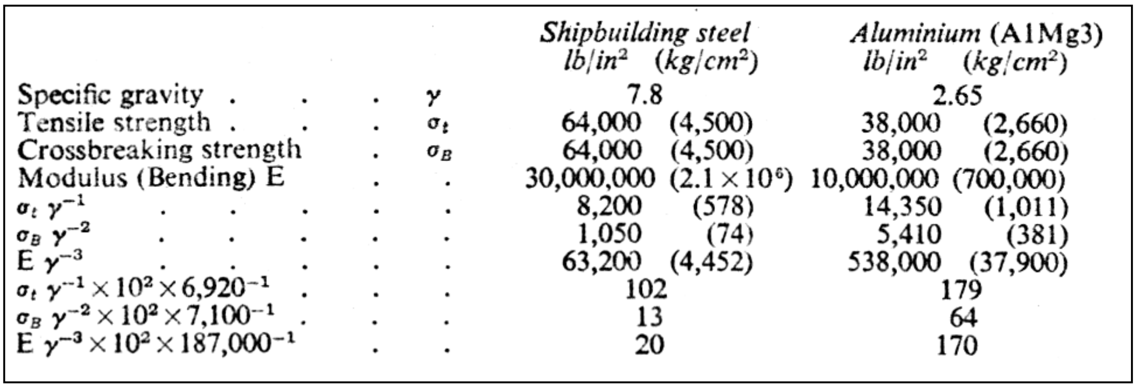
In table 3.9 and table 3.10, FRP, both with mat and with woven roving as reinforcement, is compared with steel and light alloy on the basis of equal weight and using the three criteria found above. With FRP mat as a basis, it follows:

- FRP-woven roving is stronger than aluminum, FRP-mat and steel.
- FRP-woven roving is more rigid than FRP-mat and steel.
- Aluminum is more rigid than FRP-woven roving, FRP-mat and steel.



		FRP mat (28 %) *lb/in²*	*(kg/cm²)*	*FRP woven roving* (45 %) *lb/in²*	*(kg/cm²)*
Specific gravity	γ	1.5		1.6	
Tensile strength	σ_t	12,150	(850)	31,000	(2,170)
Crossbreaking strength	σ_B	19,300	(1,350)	31,500	(2,200)
Modulus (Bending) E		1,070,000	(75,000)	1,500,000	(105,000)
$\sigma_t\ \gamma^{-1}$		8,100	(566)	19,350	(1,363)
$\sigma_B\ \gamma^{-2}$		8,580	(600)	12,250	(863)
$E\ \gamma^{-3}$		318,000	(22,250)	361,000	(25,432)
$\sigma_t\ \gamma^{-1} \times 10^2 \times 6{,}920^{-1}$		100		241	
$\sigma_B\ \gamma^{-2} \times 10^2 \times 7{,}100^{-1}$		100		144	
$E\ \gamma^{-3} \times 10^2 \times 187{,}000^{-1}$		100		114	

Table 3.9. FRP versus steel and aluminum as regard strength and stiffness-1. (Verweij 1978)



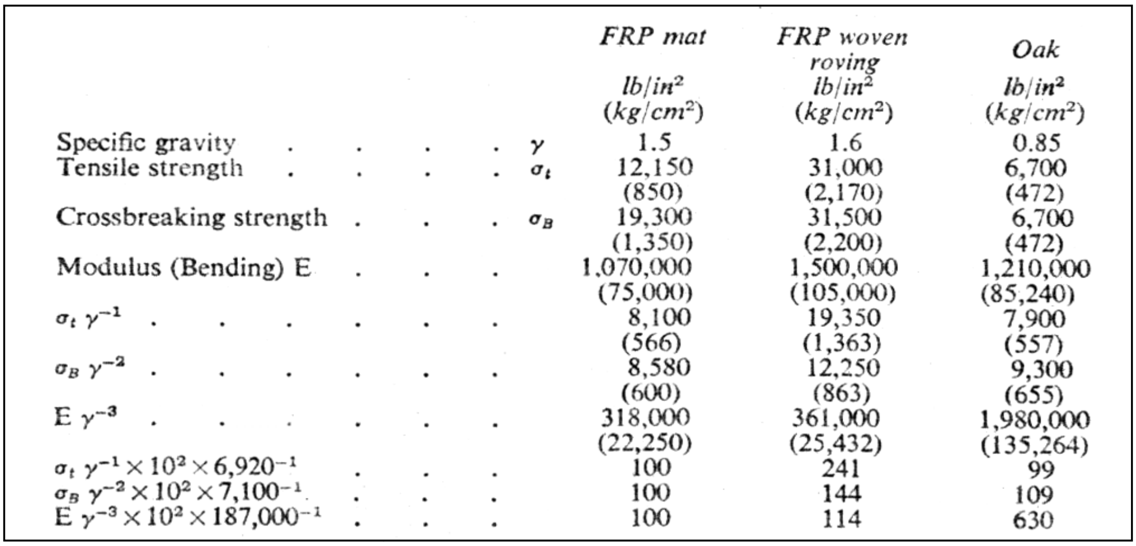
		Shipbuilding steel *lb/in²*	*(kg/cm²)*	*Aluminium* (A1Mg3) *lb/in²*	*(kg/cm²)*
Specific gravity	γ	7.8		2.65	
Tensile strength	σ_t	64,000	(4,500)	38,000	(2,660)
Crossbreaking strength	σ_B	64,000	(4,500)	38,000	(2,660)
Modulus (Bending) E		30,000,000	(2.1×10^6)	10,000,000	(700,000)
$\sigma_t\ \gamma^{-1}$		8,200	(578)	14,350	(1,011)
$\sigma_B\ \gamma^{-2}$		1,050	(74)	5,410	(381)
$E\ \gamma^{-3}$		63,200	(4,452)	538,000	(37,900)
$\sigma_t\ \gamma^{-1} \times 10^2 \times 6{,}920^{-1}$		102		179	
$\sigma_B\ \gamma^{-2} \times 10^2 \times 7{,}100^{-1}$		13		64	
$E\ \gamma^{-3} \times 10^2 \times 187{,}000^{-1}$		20		170	

Table 3.10. FRP versus steel and aluminium as regard strength and stiffness-2. (Verweij 1978)

2. Comparison of FRP with wood as regards strength and rigidity

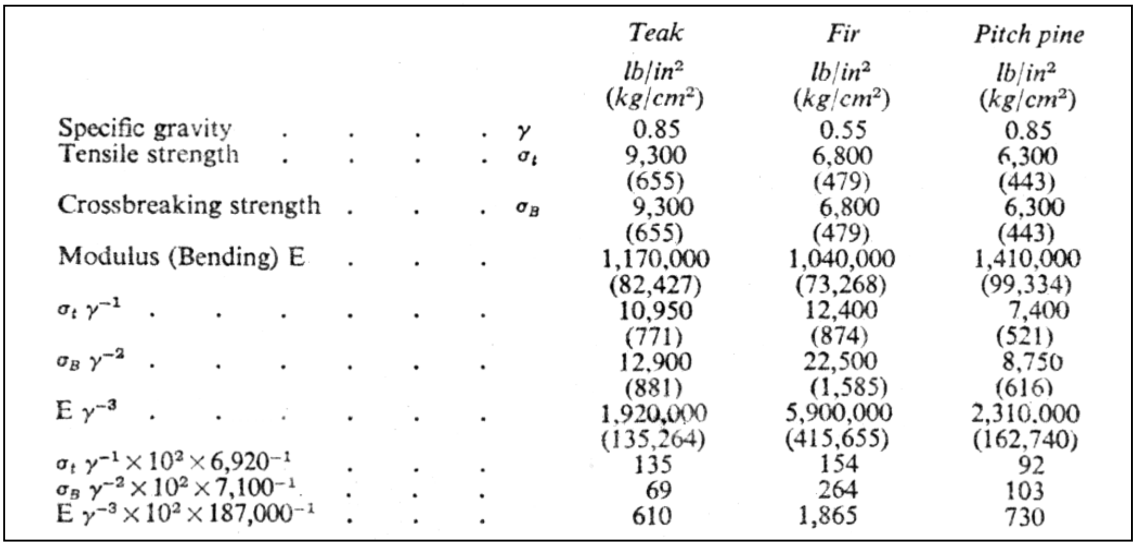
Whereas comparison of the mechanical qualities of FRP with those of steel and aluminium was rather simple, a comparison of FRP with wood is more difficult. This is because of the followings:

- Variations in mechanical qualities of various samples of same wood can differ greatly
- The mechanical qualities of wood are greatly affected by the moisture content
- A wooden boat is not a homogenous structure, but consist of great number of parts held together by frames and fastenings. These fastenings cause weak spot in the structure



		FRP mat	*FRP woven roving*	*Oak*
		lb/in² (*kg/cm²*)	*lb/in²* (*kg/cm²*)	*lb/in²* (*kg/cm²*)
Specific gravity	γ	1.5	1.6	0.85
Tensile strength	σ_t	12,150	31,000	6,700
		(850)	(2,170)	(472)
Crossbreaking strength	σ_B	19,300	31,500	6,700
		(1,350)	(2,200)	(472)
Modulus (Bending) E		1,070,000	1,500,000	1,210,000
		(75,000)	(105,000)	(85,240)
$\sigma_t \gamma^{-1}$		8,100	19,350	7,900
		(566)	(1,363)	(557)
$\sigma_B \gamma^{-2}$		8,580	12,250	9,300
		(600)	(863)	(655)
$E \gamma^{-3}$		318,000	361,000	1,980,000
		(22,250)	(25,432)	(135,264)
$\sigma_t \gamma^{-1} \times 10^2 \times 6{,}920^{-1}$		100	241	99
$\sigma_B \gamma^{-2} \times 10^2 \times 7{,}100^{-1}$		100	144	109
$E \gamma^{-3} \times 10^2 \times 187{,}000^{-1}$		100	114	630

Table 3.11. FRP versus wood as regard strength and stiffness-1. (Verweij 1978)



		Teak	*Fir*	*Pitch pine*
		lb/in² (*kg/cm²*)	*lb/in²* (*kg/cm²*)	*lb/in²* (*kg/cm²*)
Specific gravity	γ	0.85	0.55	0.85
Tensile strength	σ_t	9,300	6,800	6,300
		(655)	(479)	(443)
Crossbreaking strength	σ_B	9,300	6,800	6,300
		(655)	(479)	(443)
Modulus (Bending) E		1,170,000	1,040,000	1,410,000
		(82,427)	(73,268)	(99,334)
$\sigma_t \gamma^{-1}$		10,950	12,400	7,400
		(771)	(874)	(521)
$\sigma_B \gamma^{-2}$		12,900	22,500	8,750
		(881)	(1,585)	(616)
$E \gamma^{-3}$		1,920,000	5,900,000	2,310,000
		(135,264)	(415,655)	(162,740)
$\sigma_t \gamma^{-1} \times 10^2 \times 6{,}920^{-1}$		135	154	92
$\sigma_B \gamma^{-2} \times 10^2 \times 7{,}100^{-1}$		69	264	103
$E \gamma^{-3} \times 10^2 \times 187{,}000^{-1}$		610	1,865	730

Table 3.12. FRP versus wood as regard strength and stiffness-2. (Verweij 1978)

Therefore, a comparison on the basis of laboratory-selected samples of wood bears little relation to the characteristics of the complete wood enstructure in the boat. Nevertheless, an attempt is made to compare FRP-mat and FRP-woven roving with oak, teak, fir and pitch pine (table 3.11. and table 3.12.). The mechanical qualities of the wood are those for wet wood, taken along the direction of the grain, i.e. for wooden beams, supported and loaded as in figure 3.11.

Conclusion, on the basis of equal weight, wood (in wet condition tested as figure 3.11.) is much more rigid than FRP-mat. However, FRP-woven is stronger than wood.

3. Comparison over practical experience of FRP and other materials

The comparison of the materials as given in table 3.9.-3.14. is based on a comparison of beams out of the different materials.

It is difficult, if not impossible, to compare FRP with wood soley on the basis of the tables showing mechanical characteristics, but rather with actual experience with wooden and FRP boats, which have stood up practice, and have been built lighter than comparable wooden craft and with good result. Some examples may illustrate this.

In many countries, ship' lifeboats made of FRP have almost completely replaces former wooden, steel and aluminum boats. These FRP boats are lighter than the others, yet they are strong enough for their purpose. Only FRP lifeboats have to pass rigorous tests, amongst these a drop test, illustrated in figure 3.13. It is unthinkable that wooden lifeboats would survive such treatment.

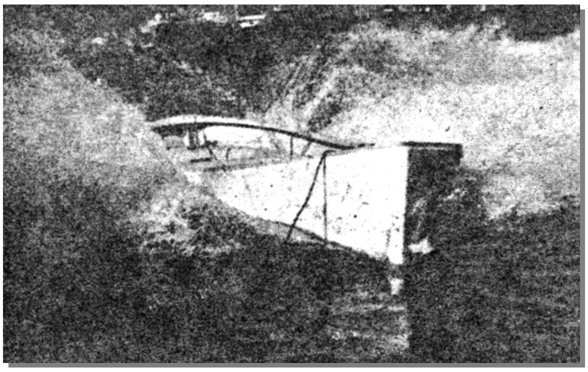


Figure 3.13. Drop test with FRP lifeboat. (Verweij 1978)

The FRP boat is stronger. In a test report, issued by police authorities after testing the prototype for some months, it was said:

"….in shallow water, on several occasion sand and stone bottoms were hit and the boat suffered no damage. Even when running full speed and with the ebb-tide the boat ran aground on a stone jetty below the water surface which brought the boat to a sudden stop. The damage done was some scratches on the hull and a dented bilge keel. Once the boat was jammed between a bigger vessel and a mooring post which led one to expect that everything would be crushed; however, after the pressure was released, the boat returned to her old shape. If this had happened to a wooden craft, it would have been irreparably damaged, whilst a steel boat would been dented severely."

Another proof of superiority of FRP over wooden boats can be found in the military field. A great number of armies are replacing or have replaced their wooden storm and assault boats by FRP. These boats can be made not only lighter for the strength required but have lower maintenance and repair costs. (Verweij 1978)

4. Comparison of FRP sandwich with other materials

When comparing FRP with aluminum, but more especially wood, it was found that although FRP was stronger, it was less stiff. This can be overcome by adopting a sandwich-type of construction. The principle of this is illustrated in figure 3.14. The inner and outer skins are held apart by core of light-weight material. For this, PVC-foam has been used with success in a great many cases.

- Outer skin 0.3 times core thickness
- Inner skin 0.2 times core thickness

In theory the skins can be much thinner, but they become so vulnerable that they little practical value.

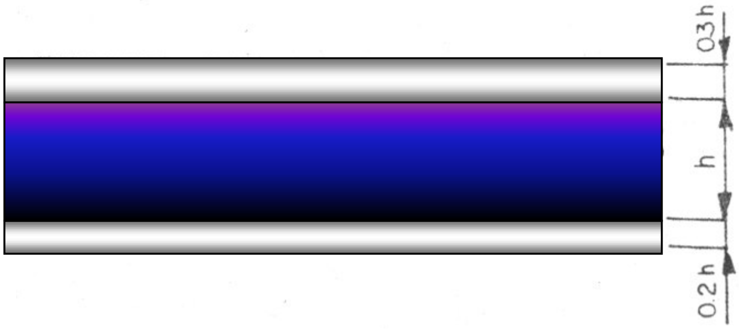


Figure 3.14. Sandwich FRP (Verweij 1978)

- **Influence of mechanical characteristics**

For the sandwich in figure 3.14., with facing of woven roving with specific gravity, 1.6 and PVC-foam core with specific gravity, 0.08, we find an overall specific gravity of 0.59.

So the sandwich with total thickness 1.5 H has the same weight as a solid FRP laminate with a thickness =1.5 H x 0.59 / 1.6=0.55 H. When calculating the moment of resistance and the moment of inertia for both the sandwich and the solid laminate, we find:

- ratio sandwich: solid of modulus of section: $0.224 H^2 / 0.05 H^2 = 4.5$
- ratio sandwich: solid moment of inertia: $0.190 H^3 / 0.014 H^3 = 13.6$

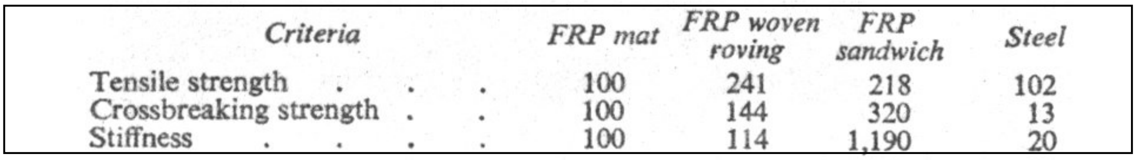
However, the bending strength of the sandwich as well as he modulus of elasticity are lower than those found for the solid laminate. For the sandwich in question we find :

6b=15,700 lb/in² (1,100 kg/ cm²)
E= 1,145,000 lb/in² (80,000 kg/ cm²)

Therefore :

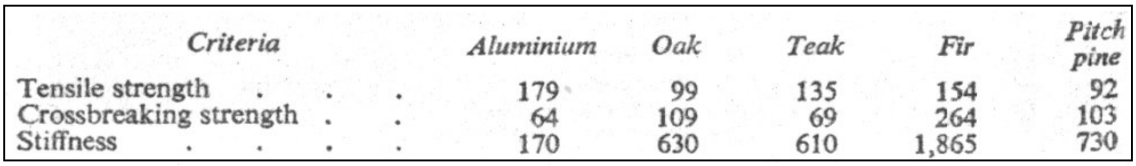
- Strength sandwich FRP / strength solid FRP = 4.5 x 15,700 / 31,500 = 2.25
- Rigidity of sandwich FRP / rigidity of solid FRP = 13.6 x 1,145,000 / 1,500,00 = 10.4

Conclusion, from table 3.13 and 3.14, it is clear that FRP sandwich is the best as regard mechanical qualities.



Criteria	*FRP mat*	*FRP woven roving*	*FRP sandwich*	*Steel*
Tensile strength . . .	100	241	218	102
Crossbreaking strength . .	100	144	320	13
Stiffness	100	114	1,190	20

Table 3.13. FRP versus other materials at equal weight-1. (Verweij 1978)



Criteria	*Aluminium*	*Oak*	*Teak*	*Fir*	*Pitch pine*
Tensile strength . . .	179	99	135	154	92
Crossbreaking strength . .	64	109	69	264	103
Stiffness	170	630	610	1,865	730

Table 3.14. FRP versus other materials at equal weight-2. (Verweij 1978)

3.6.2. Comparison of Influence of Weight

In the foregoing great stress has been laid on selecting a construction material with favourable relation of strength and stiffness for weight. It was found that FRP fulfils these requirements best. Weight is so important because of the following reasons:

- If a boat is heavy, then much material must be handled during construction, which increases building costs.
- The handling characteristic of beach-landing craft are mainly governed by weight of the boat. Above a certain weight limit, it is impossible to handle a boat alone or with two people. For a given total weight, therefore, a boat made out of a material with a high strength: weight ratio can be larger.

- It requires less power for the same speed to propel a lighter vessel, and therefore either speed may be increased or power reduced

On the other hand, it is nor necessary for a boat to heavy in order to be stable and to have good sea-keeping qualities.

In a report by the Towing Tang in Hamburg (Möckel, 1963, Verweij 1978), it was clearly proved that in comparing the stability of wooden pilot boats and FRP pilot boats, the lighter FRP boats were just as stable. Of course, and this is very important, the designer of FRP boats should take into account the influence on weight of the construction material, which he selects when determining length, beam, depth and freeboard as well when designing the lines plan of the boat in question.

3.6.3. Comparison of Impact

All wooden construction boats are rather easily damaged by impact forces; steel and more especially aluminum get severely dented or even damaged by impact forces. Steel and aluminum are moreover weakened considerably by notches or scratches. On the other hand, FRP shows excellent impact resistance, with FRP woven roving by far the best. Moreover the impact resistance values are only slightly reduced by notches. This is of great practical value. Not only will a FRP boat be able to withstand rough treatment, but also a crack once started will not continue easily as is the case with steel and aluminum.

3.6.4. Comparison of Fatigue

All of the materials mentioned in this part show reduction in strength if submitted for a prolonged time to alternating or constant forces. Both wood and FRP show fatigue strength after 10 million cycles of around 25 to 30 per cent of static strength; aluminium is the same or even less good than FRP. Steel is slightly better in this respect, since it remains about 40 per cent of its strength.

For FRP sandwich construction, a PVC-foam core may be severely weakened in case of high temperatures and is especially the case with horizontal surfaces like decks, when other core materials should be considered.

3.6.5. Comparison of Corrosion Resistance

Steel needs continuous and excellent protection to prevent rapid corrosion under salt-water condition. Some woods, especially those containing acids, such as oak and Douglas fir, may have a severe corrosive influence on steel.

Aluminium shows quite different result, depending on the type of alloy used. Some alloys show little or no corrosion in sea-water. However, aluminium remains a difficult material as regards corrosion and may give quite unexpected results. If wood, treated with preservatives containing copper, comes into contact with aluminium, this will lead to rapid corrosion. Also many antifouling paints have a disastrous effect on aluminium. Ships' life-boats have corroded completely where supported by leather-covered chocks.

With the exception of teak, all wood should be protected by proper painting to prevent rot and decay.

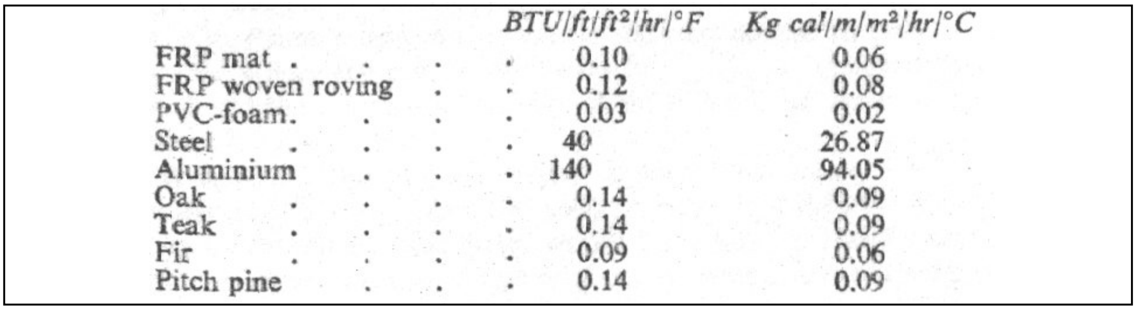
FRP is not affected by sea-water, provided proper raw material of boat-building quality have been used and have been handled with the necessary knowledge and care.

3.6.6. Comparison of Durability and Maintenance

One of the main advantages of FRP over any other material mentioned above is that it is durable, if made properly, even if unattended and without maintenance, except perhaps for a regular coat of antifouling paint.

There are several examples demonstrating this long-term durability. In a report regarding three U.S. Coast Guard boats (Cobb 1962, Verweij 1978) results of inspection of these ten-year-old boats were most encouraging. Neither sea-water (heavily polluted in this case) nor leak oil nor dirt on the inside had had any measurable effect on the laminate. Especially important was that the maintenance costs for these craft had been 80 per cent less than for comparable steel craft.

The U.S. Buships report (Graner 1960, Verweij 1978) on the superstructure of a U.S. submarine. After having been used for more than five years, the flexural strength was still 88 per cent and the flexural modulus 91 per cent of the original values. There was no change in hardness.



	BTU/ft/ft²/hr/°F	*Kg cal/m/m²/hr/°C*
FRP mat	0.10	0.06
FRP woven roving	0.12	0.08
PVC-foam	0.03	0.02
Steel	40	26.87
Aluminium	140	94.05
Oak	0.14	0.09
Teak	0.14	0.09
Fir	0.09	0.06
Pitch pine	0.14	0.09

Table 3.15. Heat conductivity. (Verweij 1978)

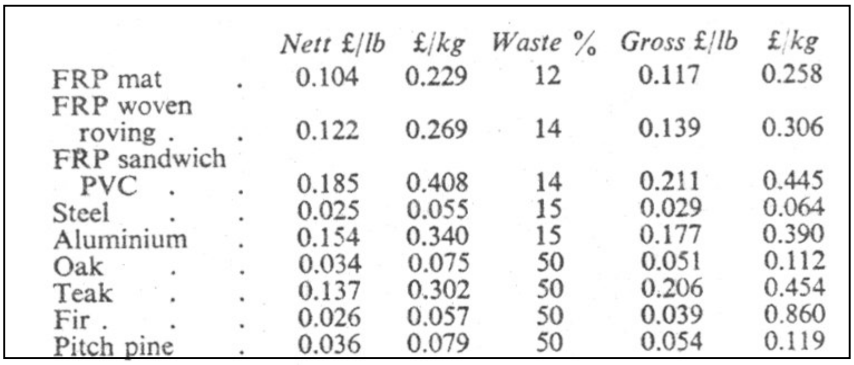
3.6.7. Comparison of Thermal Insulation

For nearly all craft, proper thermal insulation can be an important requirement. Table 3.15 shows again that FRP, especially FRP sandwich, has excellent qualities. An illustration of the heat-insulating qualities is given in the aforementioned report (Cobb, 1962). During a serious tanker fire in the port of Houston, a FRP and a steel patrol boat were despatched to the scene of the accident. The crew of the FRP boat were able to operate closer to the intense heat and for longer period than those on the steel boat, because of the low conductivity of the fibreglass boat. While the topside paint was scorched, the laminate did not ignite nor was it damaged.

3.6.8. Comparison of Cost

For a boat, especially if made sandwich, the excellent thermal insulation of FRP will make it possible to reduce drastically or leave out extra thermal insulation layers. This influences building costs favorably.

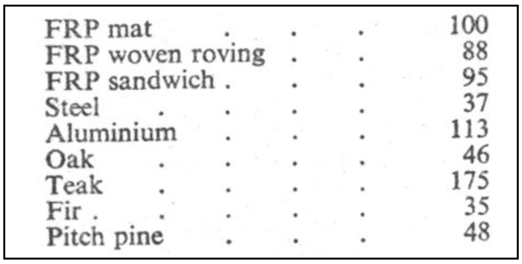
Prices of material may vary considerably according to location. Current prices in the Netherlands are given in table 3.16.



	Nett £/lb	*£/kg*	*Waste %*	*Gross £/lb*	*£/kg*
FRP mat	0.104	0.229	12	0.117	0.258
FRP woven roving	0.122	0.269	14	0.139	0.306
FRP sandwich PVC	0.185	0.408	14	0.211	0.445
Steel	0.025	0.055	15	0.029	0.064
Aluminium	0.154	0.340	15	0.177	0.390
Oak	0.034	0.075	50	0.051	0.112
Teak	0.137	0.302	50	0.206	0.454
Fir	0.026	0.057	50	0.039	0.860
Pitch pine	0.036	0.079	50	0.054	0.119

Table 3.16. Prices of materials in the Netherlands (Verweij 1978)

Taking into account, however, the differences in strength and rigidy of actual vessels, wooden construction is about 40 per cent and steel 100 per cent heavier than FRP. Table 3.17 gives an indication of the actual material costs for boats of different material.



FRP mat	100
FRP woven roving	88
FRP sandwich	95
Steel	37
Aluminium	113
Oak	46
Teak	175
Fir	35
Pitch pine	48

Table 3.17. Actual material costs for boats of different materials. (Verweij 1978)

3.6.9. Comparison of Labor Costs

The influence of labor costs on the total price of a vessel is great. Moreover, it is to be expected that this influence will increase, since almost universally they are increasing more rapidly than the cost of materials. With FRP, especially, the labor costs are influenced by several factors:

- Number of boats required
- Type of glass reinforcement
- Solid laminate, sandwich, or both
- Degree of mechanization
- Construction details
- Finish required

In many cases the designer can have a great influence on the actual labor costs and it requires much experience to design optimum boats in this respect. In view of the great number of variables, it is impossible to make a valid comparison of labor costs of FRP with other materials.

More detailed comparison between the materials over cost estimates can be found in **appendix A**.

Conclusion, material costs of FRP are by no means excessive. Labor costs of FRP vary greatly depending on design and the number of boats required. Provided they can be made in sufficient quantity, experience in different countries indicates that in many cases FRP boats are not more expensive, and often cheaper, than boats of other materials.

3.6.10. Summary of Comparison

The potential advantages of FRP over other materials for small craft construction are as follows:

Resistance to the marine environment: FRP does not corrode, rot or otherwise deteriorate when exposed for extended periods o salt air or water. It is equally unaffected by fuels or pollutants often found in rivers and harbors. Conventional FRP will become fouled with grass and barnacles as readily as wood or metal and requires antifouling bottom paint in salt or brackish water.

Light weight: With proper design and control in the shop, FRP marine structures can be fabricated that are about one-half the weight to equivalent steel or wood structures and about equal in weight to equivalent aluminum structures.

High Strength: The inherent of FRP is quite high relative to its weight, and long exposure to a marine environment has little effect on its properties.

Seamless Construction: FRP hulls are generally fabricated as a one-piece leak proof molding without seam or laps.

Chemically Inert: FRP is not affected by salt water or most chemicals associated with a marine environment, and is not susceptible to electrolysis.

Ability to Orient Fiber Strength: The nature of FRP reinforcement permits the glass fibers to be oriented in the direction of maximum stress, providing the designer with the ability to economically optimize strength-weight relationship to greater extent than with metals.

Ability to Mold Complex Shapes: FRP materials can be molded into a wide variety of complex shapes with relative ease and economy.

Flexibility: The low modulus of elasticity of FRP is beneficial in absorbing energy from impact loads such as slamming. However, this flexibility can also be a design constraint where deflections are critical.

Competitive Cost: Although the cost per pound of FRP materials is usually considerably higher than wood or steel, the over-all cost of an FRP boat is usually only slightly higher than the equivalent wood or steel hull providing the number of hulls being built in FRP are sufficient to amortize the cost of molds and other tooling. Higher costs are to be expected for prototype or one of a kind FRP hulls. FRP is generally competitive with, or slightly cheaper than, aluminum construction for high-volume production of larger boats, and may be nearly competitive for limited production.

Ability to Mold in Color: The plastic used to form FRP laminates can be provided in wide variety of colors which eliminate the need to paint the boat for many seasons. Eventually, however, the color may fade or chalk, requiring cosmetic painting.

Repairs: FRP structures are relatively easy to repair.

Low Maintenance: The non-corrosive nature of FRP generally results in much lower hull maintenance for smaller craft. The corresponding savings for larger hulls may be less since antifouling painting is required at the same intervals as with hulls of other materials, and painting of topsides will eventually be required to cover up scrapes, gouges and color fading.

Durability: Surveys of U.S. Navy and U.S. Coast Guard small boats and pleasure craft indicate no degradation in laminate properties after as long as 20 year service. With proper maintenance and reasonable care FRP boats would appear to have an indefinite life.

These advantages are offset by a number of potential problems, which must be considered in designing FRP boats, including the following:

Stiffness: The modulus of elasticity of conventional FRP laminates is usually less than 2x 10^3x10^3 PSI, compared to 30 x 10^3x10^3 for steel and 10x 10^3x10^3 PSI for aluminum. The use of unidirectional FRP laminates with greater percentage of the glass oriented in the direction of the load or higher strength glass/ carbon composites can increase the modulus to about 4 to 6 x 10^3x10^3 PSI, but FRP is still at a disadvantage in deflection-critical application.

Hull Strength: Although the basic short-term strength of FRP is quite satisfactory, its relative fatigue strength is somewhat lower than metals, which must be consider in selecting design loads and safety factors. In addition, the notch toughness of FRP structures must be evaluated to determine the problems associated with stress concentrations such as at hatch corners, endings of stiffeners or decks, and other discontinuities. The low buckling strength of FRP also warrants consideration in evaluating the basic structural concepts.

Creep: FRP has a tendency to creep if subjected to long-term loading and if the laminate stresses are high, though this is not a problem for normal boat structures.

Vibration: The low modulus of elasticity of FRP may lead to problems with structural vibrations, particularly in way of reciprocating machinery and propellers, if adequate stiffness is not provided.

Abrasion: The abrasion resistance of FRP is less than that of metals, though better than wood, and necessitates the use of bumpers or chafing plates in areas where abrasive loads might occur.

Vulnerability to Fire: The conventional FRP laminate is fabricated with a type of resin, which is flammable and will support combustion with about the same intensity and flame-spread rate as plywood. There are fire-retardant types available, which are self-extinguishing after removal of the source of flame, though they are still combustible to some degree, and the laminates rapidly lose strength at high temperatures. The fire-retardant resins also generate toxic fumes in the presence of fire. However, FRP has very good fire containment capabilities and, if properly insulated or protected can perform satisfactorily in a fire environment. (Scott 1996)

FRP is the dominant material in small boat construction and this indicates that its advantages greatly overshadow the disadvantages. The extensive experience gained in designing, building and operating FRP boats over the past 50 years has produced satisfactory and economical means of designing around the material’s characteristic.

CHAPTER 4

MANUFACTURING PROCCESS AND CONSTRUCTION TECHNIQUES OF FRP RECREATIONAL BOATS

A wide range of different processes have developed for molding of composites parts ranging from very simple manual processes such as hand lay to highly industrialized processes such as SMC (Sheet Molding Compound) molding. Each process has its own particular benefits and limitations making it applicable for particular applications. The choice of process is important in order to achieve the required technical performance at an economic cost.

The main technical factors that govern the choice of process are the size and shape of the part, the mechanical and environmental performance and aesthetics. The main economic factor is the number of identical parts required or run length.

This chapter will focus on the production techniques of FRP recreational boats both conventional such as hand lamination and spray lamination and more industrialized techniques such as vacuum bag, resin transfer molding and SMC, etc. Beside production techniques, mold building and equipments used in construction will be mentioned.

4.1. History of Boat Construction

FRP was used initially for boat construction shortly after World War II. Among the first were a series of 28 foot U.S. Navy personnel boats. Since then, the navy continued to rely heavily on FRP for construction of thousand of small boats from 12 feet to 50 feet in length including landing craft, utility and personnel boats, line handling boat is the 31 foot PBR River Patrol Boat, which saw extensive service in Southeast Asia.

The U.S. Coast Guard has employed FRP for the construction of a wide variety of utility and patrol boats up to 40 feet in length. Examination of early FRP 40 footer in 1972 which had seen nearly 20 years of continuous service showed her hull laminate to be in excellent condition, with no apparent degradation in structural properties.

After successful experiences of FRP boats in navy and coast guard, FRP started to appear in civil boats such as runabout and sailboats. Today vast majority of powerboats and sailboats built in most country are fiberglass construction

The highly competitive nature of the pleasure boat industry result in numerous design and production innovations to improve the performance and reduce the cost of the fiberglass structures, including the concept of a drop-in molded FRP hull liner into which berths, galley components and decorative surface are integrally molded. This concept greatly reduces the time and cost of fitting out the boat. Other innovations included molded-in buoyancy foam and non-skid deck patterns and one-piece molded bottom grillages. The ability to easily mold complex shapes permitted the economic development of a number of new hull forms such as the cathedral and trihedral hulls, which would be extremely difficult to shape in either wood or metal.

The introduction of carbon, graphite, aramid and other high performance fibers developed initially for the aerospace industry. These developments have opened up new opportunities for composite structures. Many offshore racing powerboats and high performance sailboats incorporate such materials in the hull and spars to achieve strength to weight rations not possible with other materials.

The development of large fiberglass fishing trawlers began in 1960 in South Africa with construction of series of 63-foot long pilchard trawlers. The success of vessels led to parallel developments in the United States. The first such vessel was the 72 foot trawler R.C. BRENT, launched in Florida in 1968. This led to several builders marketing FRP shrimp trawlers about 75 feet long. Service experience with these boats is excellent. The largest FRP fishing trawler in series production was a 93 foot purse seiner being built in Peru. Early studies indicate the feasibility of FRP trawlers up to 110 feet long and there is no reason to believe that this is the upper limit on size.

The development of FRP minesweepers was begun simultaneously by the United States and British Navies in the early 1960’s. The non-magnetic nature of FRP makes it an ideal material for such a vessel, since it is both lighter and lower in life cycle cost than conventional wood construction. Initial U.S. Navy studies, indicated the feasibility of building FRP minesweepers up to about 190 feet long and led to the construction of a full scale midship section which was tested for acoustic characteristics and shock resistance in 1970. The British studies and tests were sufficiently successful that a prototype 153-foot FRP mine hunter was completed in January 1972. This was followed by the HUNT and SANDOWN classes for the Royal Navy, and the Italian

LERICI and GAETA classes. The U.S. Navy's OSPREY class minehunter, derived from the GAETA class, is 188 feet long and displaces 890 tons, and is the largest FRP ship in production at this time.

Recent U.S. Navy studies demonstrated the feasibility of using FRP for construction of a 1200 ton corvette, and extensive studies are now being directed toward the use of FRP for the deck-houses on large ships. One of the features of FRP that is of interest is ability to mold in materials that will reduce the radar signature of the ship. (Scott 1996)

FRP has been used for number of other marine applications over years including submarine fairwaters and sonar domes, deck-houses, tanks, masts, hatch covers, etc. These applications are generally based upon the lightweight, corrosion resistance and durability of FRP.

It is expected that fiberglass will continue to maintain a dominant position in small boat construction in the future, including a greater percentage of the one-off or limited production market where other materials have historically had a competitive cost advantage. This is due to recent developments in limited-production technology, which have substantially reduced the cost of tooling.

4.2. Mold Building

Mold is the main part of the FRP boat construction. It can be female or male, as shown in figure 4.1. Almost all production hull fabrication is done with female molds that enable the builder to produce a number of identical parts with a quality exterior finish. It is essential that molds are carefully constructed using the proper materials if consistent finish quality and dimensional control are desired.

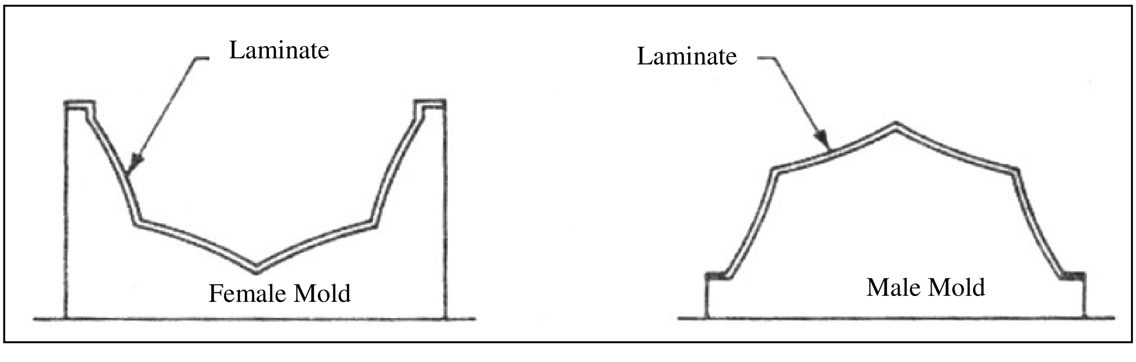


Figure 4.1. Female (negative) and Male (positive) molds. (Scott 1996)

A mold is built over a plug that geometrically resembles the finished part. The plug is typically built of non-porous wood, such as oak, mahogany or ash. The wood is then covered with about three layers of 7.5 to 10 ounce cloth or equivalent thickness of mat. The surface is faired and finished with a surface curing resin, with pigment in the first coat to assist in obtaining a uniform surface. After the plug is wet-sanded, three coats of carnauba wax and a layer of PVA parting film can be applied by hand.

The first step of building a mold on a male plug consists of gel coat application, which is a critical step in the process. A non-pigmented gel coat that is specifically formulated for mold applications should be applied in 10 mil layers to a thickness of 30 to 40 mils. The characteristics of tooling gel coats include: toughness, high heat distortion, high gloss and good glass retention. A back-up layer of gel that is pigmented to a dark color is then applied to enable the laminator to detect air in the production laminates and evenly apply the production gel coat surfaces.

Molds can either be one piece or split along the centerline. The one piece of mold is simpler to construct and maintain but requires that the hull be lifted clear of the mold after completion. For small boats, this is not problem, but for larger hulls heavy chain falls or other lifting apparatus is required, and the height of the molding area must be at least twice that of the part, unless the mold is placed in a pit. The split mold avoids this problem, since the two halves can be moved outward and the completed hull moved longitudinally without lifting. The disadvantages of the split mold are the necessity of bolting the two halves together for layup and the greater amount of floor space required to permit moving the mold halves.

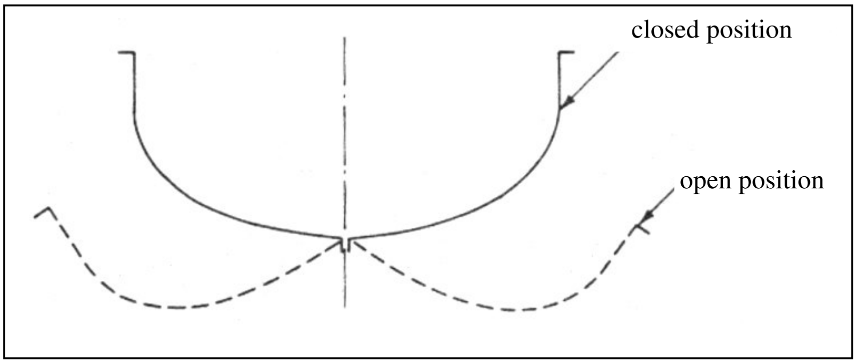


Figure 4.2. Hinged split mold. (Scott 1996)

Split molds are sometimes hinged along the centerline so that the two halves can be layed flat as shown in Figure 4.2. This provides the advantages of being able to lay up the laminate in a down hand position, minimizing the problem of resin drainage from vertical surfaces. The basic disadvantages is that a heavy bridging laminate must be layed up along the centerline to join the two halves of the hull after cure. (Scott 1996)

Figure 4.3. Shows molding. A- Firstly, the pattern is made (1), accurate in size and detail, as nearly perfect finish as possible. Over this, the fiberglass mold is made (2), the exact negative of the pattern. The gel coat, applied on mold, (3) picks up the perfect finish of the pattern. B- The fiberglass mold is inverted and then in this negative shape, the product is molded (4), with the exact shape and surface finish of the pattern. Now the gel coat (5) is outside.

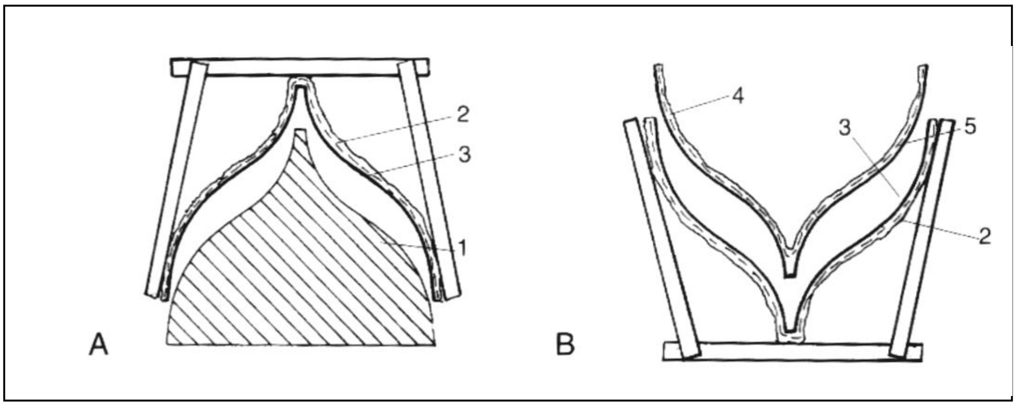


Figure 4.3. Molding: Pattern-negative mold-molding (Plessis 1996)

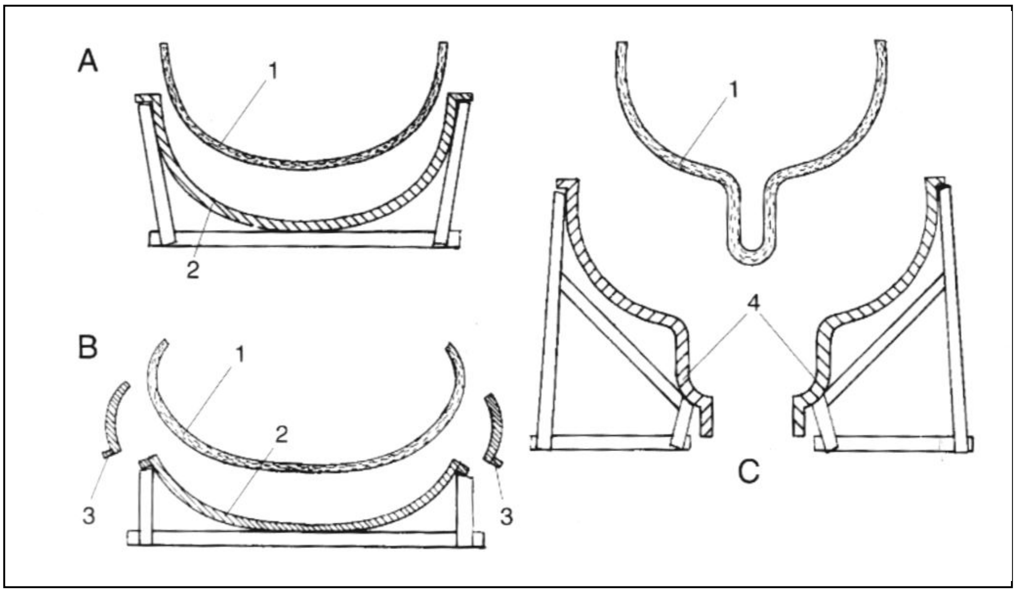


Figure 4.4. Mold types. (Plessis 1996)

Figure 4.4. Shows different mold types. **A**- A simple shape (1) will release from the negative mold (2), easily as it is a straight draw. **B**- If there are undercuts a straight draw is impossible. So the portion causing the undercut (3), must be detachable. **C**-

Deep shapes are also difficult to release, so these are often made in a mold, which split along the centerline (4), this makes molding easier too.

4.2.1. Planked Wood Mold

This female mold consist of an inexpensive planked form layed up over a wood framework, sanded smooth, surfaced with fiberglass and finished to the desired surface. In a sense, this mold is a conventional wood built inside-out. As an alternative, a male form can be built, similar to wood boat built upside down. This precludes the requirement for carefully finishing the surface of the mold, since it would be the inner surface of the hull, but it requires that the outer non-mold surface of the be sanded and also requires that the hull be turned over. Another alternative is to use plywood in lieu of planking to surface the form in relatively flat areas. The fundamental advantage of this mold is elimination of the plug, though it lacks the dimensional stability and long life of a conventional mold.

Figure 4.5. Production Female Mold on Spindle at Corsair Marine (Greene 2004)

Figure 4.6. Metal Stiffened Female Mold at North coast Yachts (Greene 2004)

Figure 4.7. Batten Construction of Female Mold at Westport Shipyard (Greene 2004)

4.2.2. Integral or “lost” Mold

This technique can be used for laying up hulls for sandwich construction. An inexpensive open wood framework is “planked” with strips of PVC foam, which are nailed lightly to the framework. The foam is then covered with fiberglass, which is allowed to cure. The assembly is inverted, the framework removed and the inner skin of fiberglass is layed up. This technique requires that the outer surface of the hull be sanded or ground to achieve the desired surface finish.

4.3. Equipment used in boat construction

Various manufacturing equipment is used to assist in the laminating process. Most devices are aimed at either reducing man-hour requirements or improving manufacturing consistency.

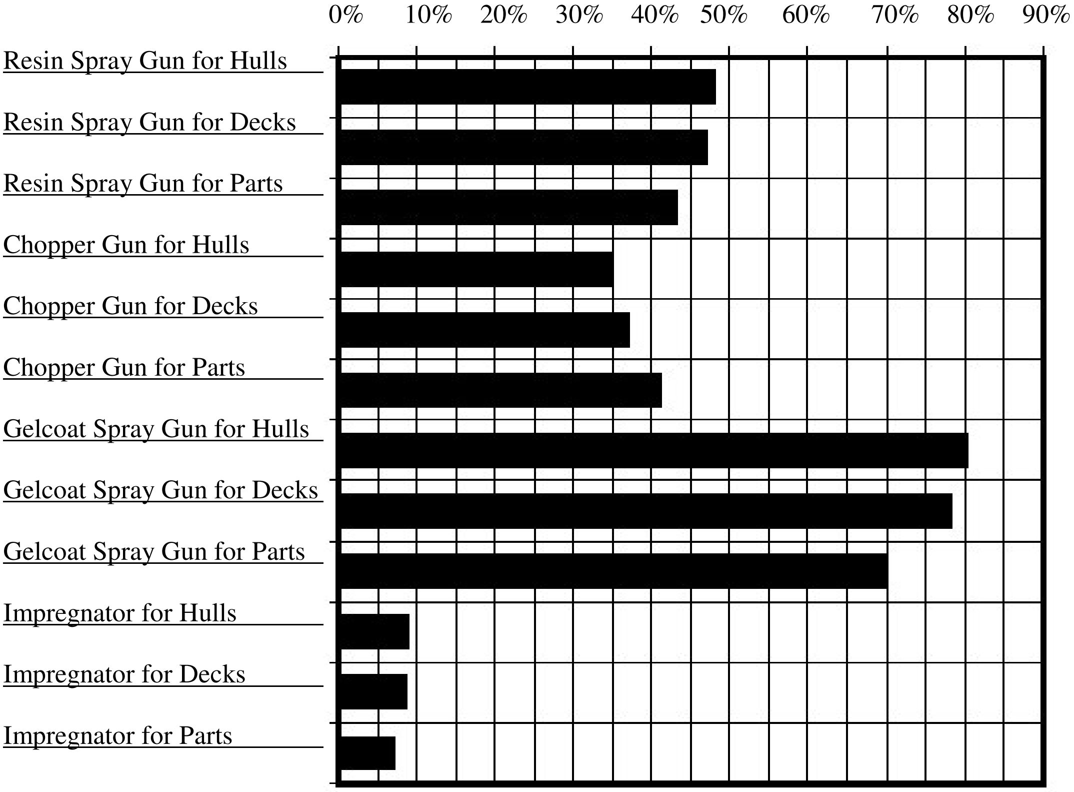


Figure 4.8. Manufacturing Equipment (Greene 2004)

Bucket and Brush: The bucket and brush technique is the oldest method of applying resin to fiberglass reinforcements. Individual batches of resin are mixed with a catalyst in a bucket or pail and applied to the part using a brush or paint roller. This technique was the first method used in fiberglass boat manufacturing until spray equipment and chopper guns were developed for applying resin.

Currently, it is used only in limited cases for low volume production or custom work or for fabricating and bonding small parts at larger production facilities.

The advantages of this technique compared to spray application in addition to emission reductions are:

- Reduced worker exposure to styrene because the resin is not atomized; and
- No special equipment is needed so this process can be used by small shops or in situations in which other application equipment is not available, such as for assembly outside a laminating shop or for repair of existing boats.

Most boat manufacturers, except those making very small boats such as canoes and kayaks and a few other specialized types of boats, have switched to other resin application techniques because mixing batches of resin and catalyst is labor-intensive and inefficient compared to other methods. In addition, the buckets and excess resin can become a significant amount of solid waste and also wasted materials.

Resin Rollers: Resin rollers consist of a fabric roller that is fed a continuous supply of catalyzed resin from a mechanical fluid pump. The fluid pump draws resin from a drum or bulk distribution line. The resin pump is mechanically linked to a separate catalyst pump. These two pumps supply the resin and catalyst in a predetermined but adjustable ratio to a static mixer located in the handle of the roller. The static mixer then feeds the catalyzed resin to the roller head through the handle of the roller. Since atomization is not required with resin rollers, resin delivery pressures are below the delivery pressure of most resin spraying systems.

A valve controlled by the operator regulates the amount of resin flowing to the roller head and to the part being fabricated. The resin flow is distributed to the roller head by a manifold within the roller head. A typical roller head is about 9 inches wide by 1.5 inches in diameter and has about 150 holes that are about 1/32 inches in diameter. The roller head is covered with a disposable fabric cover similar to a standard paint roller cover. This arrangement distributes the resin uniformly around the circumference of the roller. Resin rollers are intended to be operated more or less continuously during a shift to prevent the resin from hardening between the static mixer and the roller cover.

At the end of the shift, the roller cover is discarded and the mixing unit, handle, and roller manifold are flushed with a solvent. Non-HAP, non-VOC solvents can be used for solvent flushing.

Resin rollers are used to manufacture a range of boats from 12 to 40 feet in length, including both sail and power boats.

Resin rollers have the following advantages compared to resin spray application systems:

- A higher transfer efficiency than spray systems with more resin going onto the part and less resin being lost as overspray;
- Reduced need for personal protective equipment, including respirators and coveralls;
- A cleaner and more comfortable work environment, including reduced consumption of disposable floor coverings;
- More control over final part weight and reduced variability among parts; and
- As a control option, resin rollers can be combined with low-styrene resins for additional emission reductions.

Several issues have been raised with respect to resin rollers as an emission control option.

- Switching to resin rollers from spray equipment will require capital costs to purchase the resin rollers and possibly modify the existing resin distribution and pumping equipment;
- Resin rollers may have higher maintenance costs compared to spray equipment;
- Resin rollers can be difficult to work into narrow spaces and tight corners and small parts may require that the fabric is impregnated with resin before it is placed in the mold;
- The longer handles on resin rollers may be difficult to maneuver around the scaffolding used for working inside larger hulls;

- Work must be scheduled to keep the roller in more or less continuous use throughout a shift to prevent resin from hardening inside the handle and roller head;
- Resin rollers may require more cleaning solvent and generate more waste solvent than external mix spray equipment; and
- Resin rollers may dispense resin at a slower rate than resin spray equipment and this may lead to slower production.

Flow Coaters: Flow coaters are similar to standard resin spraying equipment except that the resin leaves the tip of the flow coater in continuous consolidated streams rather than as an atomized spray. Whereas the tip of a spray gun is a single small orifice, the tip of a flow coater has a dozen or so precisely drilled holes that produce steady streams of resin, similar to a small showerhead. At least one manufacturer produces an internal-mix resin spray gun that can be converted to a flow coater simply by switching the nozzle from a single orifice tip to a flow coater nozzle. Flow coaters can also be fitted with a chopper head to apply chopped fiberglass roving in the same way as a conventional atomized chopper gun.

The flow coaters use the same resin and catalyst pumps that are used with catalyst-injected spray equipment or resin rollers. The fluid pump draws resin from a drum or bulk distribution line. The resin pump is mechanically linked to a separate catalyst pump. These two pumps supply the resin and catalyst in a predetermined but adjustable ratio to a static mixer located in the handle of the flow coater. The static mixer then feeds the resin to the flow coater head through the handle of the flow coater. A valve controlled by the operator regulates the amount of resin being applied to the part being fabricated. Flow coaters are operated at a lower fluid pressure than resin spray equipment.

Like resin rollers and other internal mix equipment, flow coaters are intended to be operated more or less continuously during a shift to prevent the resin from hardening inside the applicator. At the end of the shift, the mixing unit, handle, and nozzle are flushed using a solvent recirculated in a closed system.

Flow coaters and chopper flow coaters are used to manufacture both power and sailboats up to about 40 feet in length.

Flow coaters have the following benefits over resin spray application systems and as an emission control option.

- A higher transfer efficiency than spray systems with more resin going onto the part and less resin being lost as overspray;
- Reduced need for personal protective equipment, including respirators and coveralls (one manufacture has noticed that the employees are able to work closer together and faster than if using spray guns);
- A cleaner and more comfortable work environment, including reduced consumption of disposable floor coverings; and
- As a control option, flow coaters can be combined with low styrene resins for additional emission reductions.

Several issues have been raised with respect to using flow coaters as an emission control option:

- Flow coaters may dispense resin at a slower rate than resin spray equipment and this may lead to reduced production;
- Switching or converting spray equipment to flow coaters will require capital expenditures; however, these costs can be relatively modest depending on the spray equipment currently used;
- Higher maintenance costs compared to spray equipment (Thoroughbred Powerboats reported that flow coaters increased valve maintenance costs approximately 5 times compared to spray gun systems);
- Some industry representatives have stated that flow coaters may not be able to shoot as far as conventional spray equipment and it may be harder to laminate from outside large molds with flow coaters;
- Work must be scheduled to keep the flow coater in use more or less continuously throughout a shift to prevent resin from hardening inside the application equipment; and
- Flow coaters may require more cleaning solvent and generate more waste solvent than external mix spray equipment.

Figure 4.9. Flow coater WEB_18 (2004)

Chopper Gun and Spray-Up: A special gun is used to deposit a mixture of resin and chopped strands of fiberglass filament onto the mold surface that resembles chopped strand mat. The gun is called a “chopper gun” because it draws continuous strands of fiberglass from a spool through a series of whirling blades that chop it into strands about two inches long. The chopped strands are blown into the path of two streams of atomized liquid resin, one accelerated and one catalyzed (known as the two-pot gun). When the mixture reaches the mold, a random pattern is produced.

Alternately, catalyst can be injected into a stream of promoted resin with a catalyst injector gun. Both liquids are delivered to a single-head, dual nozzle gun in proper proportions and are mixed either internally or externally. Control of gel times with this type of gun is accomplished by adjusting the rate of catalyst flow. Spray systems may also be either airless or air-atomized. The airless systems use hydraulic pressure to disperse the resin mix. The air atomized type introduces air into the resin mix to assist in the dispersion process. Figures 4.10. and 4.10. illustrate the operation of air-atomizing and airless systems.

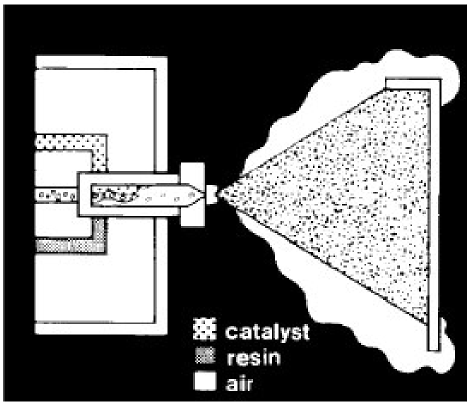


Figure 4.10. Air Atomizing Gun (Greene 2004)

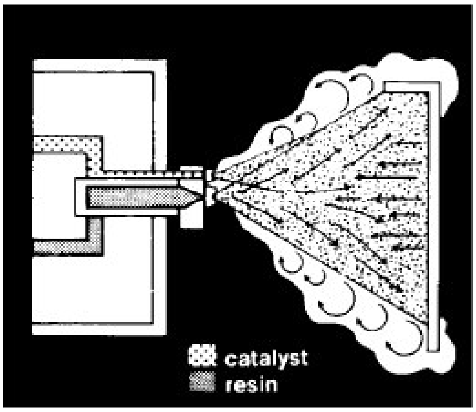


Figure 4.11.Airless Spray Gun (Greene 2004)

Resin and Gel Coat Spray Guns: High-volume production shops usually apply resin to laminates via resin spray guns. A two-part system is often used that mixes separate supplies of catalyzed and accelerated resins with a gun similar to a paint sprayer. Since neither type of resin can cure by itself without being added to the other, this system minimizes the chances of premature cure of the resin.

This system provides uniformity of cure as well as good control of the quantity and dispersion of resin. Resin spray guns can also be of the catalyst injection type described above. Air atomized guns can either be the internal type illustrated in Figure 4.13. or the external type shown in Figure 4.14.

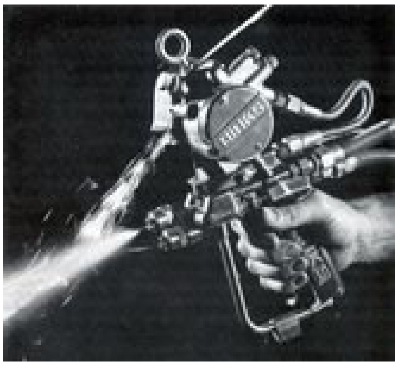


Figure 4.12. Spray Gun WEB_18 (2004)

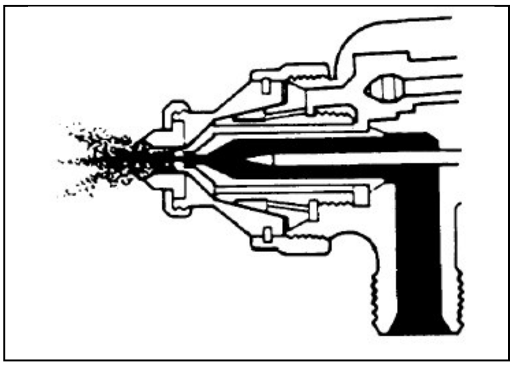


Figure 4.13.Internal Atomization Spray Gun (Greene 2004)

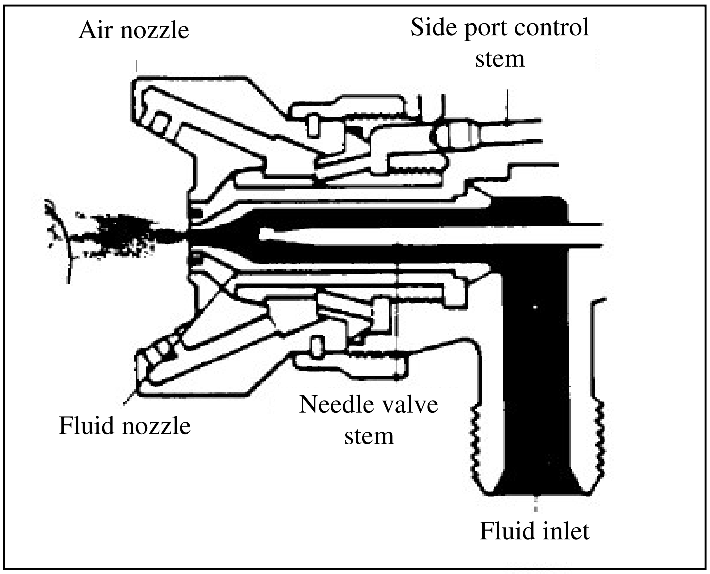


Figure 4.14. External Atomization Spray Gun (Greene 2004)

Impregnator: Impregnators are high output machines designed for wetting and placing E-glass woven roving and other materials that can retain their integrity when wetted. These machines can also process reinforcements that combine mat and woven roving as well as Kevlar ®.

Laminates are laid into the mold under the impregnator by using pneumatic drive systems to move the machine with overhead bridge-crane or gantries. Figures 4.16. and 4.17. show a configuration for a semi-gantry impregnator, which is used when the span between overhead structural members may be too great.

Roll goods to 60 inches can be wetted and layed-up in one continuous movement of the machine. The process involves two nip rollers that control a pool of catalyzed material on either side of the reinforcement. An additional set of rubber rollers is used to feed the reinforcement through the nip rollers and prevent the reinforcement from being pulled through by its own weight as it drops to the mold. Figure 4.15. is a schematic representation of the impregnator material path.

Impregnators are used for large scale operations, such as mine countermeasure vessels, 100 foot yachts and large volume production of barge covers. In addition to the benefits achieved through reduction of labor, quality control is improved by reducing the variation of laminate resin content. High fiber volumes and low void content are also claimed by equipment manufacturers.

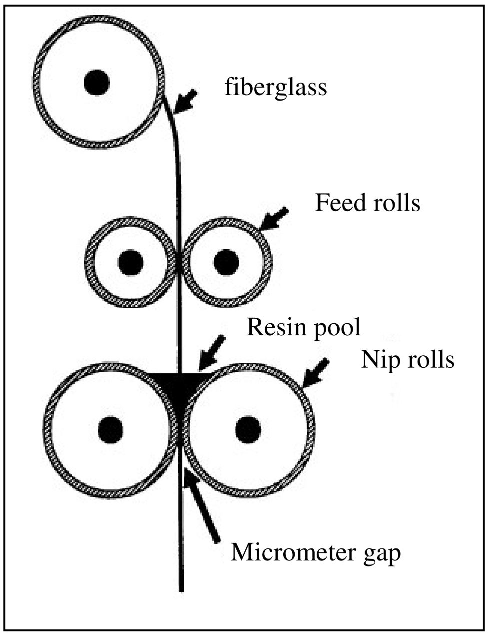


Figure 4.15. Impregnator Material Path (Greene 2004)

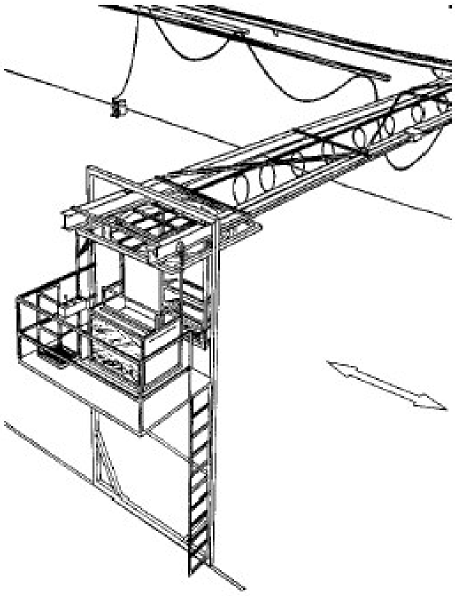


Figure 4.16. Configuration of Semi-Gantry Impregnator (Greene 2004)

Figure 4.17. Impregnator (Greene 2004)

Resin impregnators have the following advantages over resin spray application systems in addition to reduced emissions:

- Minimizes worker exposure to styrene and resin and makes for a cleaner shop environment because resin is not being spray-applied;
- Impregnators may be faster and require less labor in situations in which many layers of fabric need to be applied over a large part; and
- The builder has more control over the fiber-to-resin ratio than most other systems so impregnators may improve the quality and consistency of the laminate.

There are several issues associated with using fabric impregnators over other types of resin application systems.

- Fabric impregnators are generally not very mobile unless they are mounted on a cart or a bridge crane;
- It is necessary to move the saturated fabric from the impregnator to the part and this may offset some of the initial labor savings;
- Fabric impregnators can be difficult to clean and must be operated continuously to prevent resin from hardening on them; and

- Switching to fabric impregnators would involve some capita expenditures; basic units start at about $10,000.

Figure 4.18. Laminators Consolidate Reinforcement Material Applied by Impregnator at Westport Shipyard. (Greene 2004)

4.4. Structural Concepts

Early fiberglass boat building produced single-skin structures with stiffeners to maintain reasonable panel sizes. Smaller structures used isotropic (equal strength in x and y directions) 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.

In the early 1970s, designers realized that increasingly stiffer and lighter structures could be achieved if a sandwich construction technique was used. By laminating an inner and outer skin to 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. Linear and cross-linked PVC foam and end-grain balsa have evolved as the primary core materials.

The most popular forms of open molding in the marine industry are single-skin from female molds, cored construction from female molds and cored construction from male mold. Industry survey results showing the popularity of these techniques is shown in Figure 4.19.

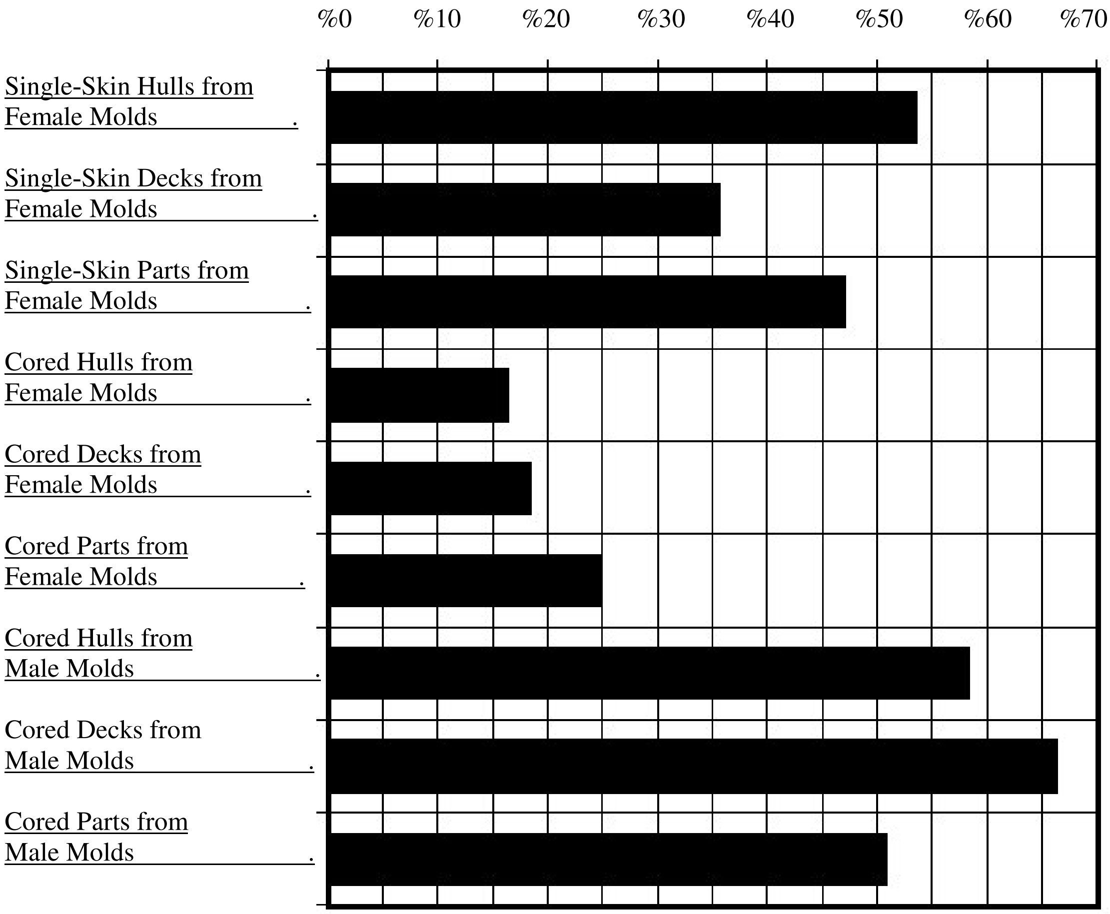


Figure 4.19. Marine Industry Construction Methods (Greene 2004)

Figure 4.20. Shows the differences in stiffness, strength, and weight when a core material is placed between the plies of a single skin laminate (all attributes are approximately normalized).

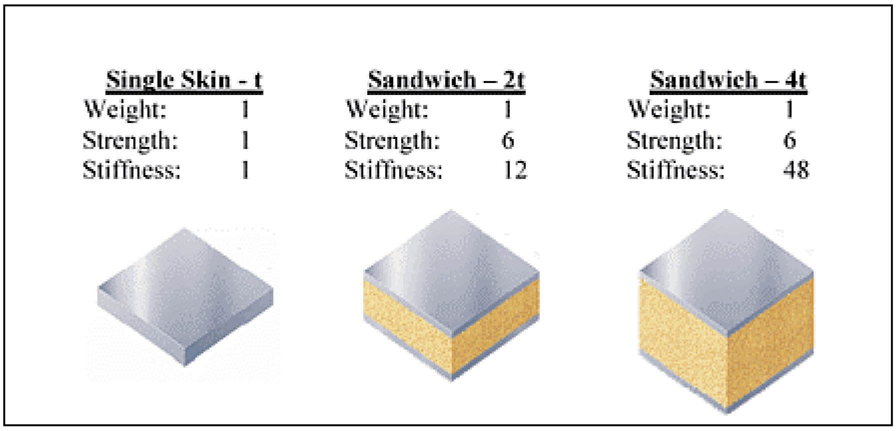


Figure 4.20. Comparison of properties (single skin and sandwich construction) WEB_10 (2004)

4.4.1. Single Skin Construction

Single skin construction is similar to conventional wood and metal construction. It utilizes a single thickness of fiberglass laminate supported by frames whish reduce panel sizes and provide overall rigidity to the hull. This construction is considered the most simple to fabricate and used extensively for shells, where it derives considerable strength from the curved shapes found in most small boat hulls.

Framing: The framing system used to support the single skin can be either longitudinally or transversely oriented, or combination of both orientations. In general longitudinal framing is favored for the bottom of powerboats and utilizes engine stringers as the main supporting members. The longitudinal stringers are supported by either transverse floors or bulkheads which in turn transverse the loads to the side-shell in shear. The sideshells of powerboats are usually unstiffened since the combination of shape, built-in berths and other furniture and bulkheads provide sufficient strength. If framing is required, transverse framing is generally shallower in depth, and causes less interference with internal arrangements. On the other hand, transverse framing is usually heavier than longitudinal framing and can not be as easily integrated with build-in furniture.

The hulls of sailboats usually have relatively little framing due to their pronounced shape. In larger keel boats it is usually necessary to provide at least two bottom longitudinals tied into a series of transverse floors to support the keel.

There is a lot of framing system used by boatbuilding industry. A few of the more common types are shown in Figure 4.21. and include the following:

1. Conventional hat section:, in which a non-structural foam core in bonded in place and successive layers of reinforcement are layed over the core and overlapped onto the skin. Variations on this type include the use of very light premolded plastic or FRP hollow formers in lieu of foam for core.

2. Hat section with flange doubler: Similar to the hat section described above, but with a number of layers of unidirectional reinforcement on the top flange to increase strength and stiffness.

3. Encapsulated wood or plywood: This type of stiffener must be designed for the strength of the wood, since the elastic moduli of wood and FRP are similar. Therefore the FRP is primarily for protection and attachment to the skin. The use of encapsulated wood is questionable in the bottom of boats because of possible problems with rotting and swelling if the wood gets wet. However this is fairly common practice in the industry, trough most builders use plywood rather than timber because of its better dimensional stability. With wood-cored stiffeners it is important to properly scarph and overlap joints in the wood to maintain full strength.

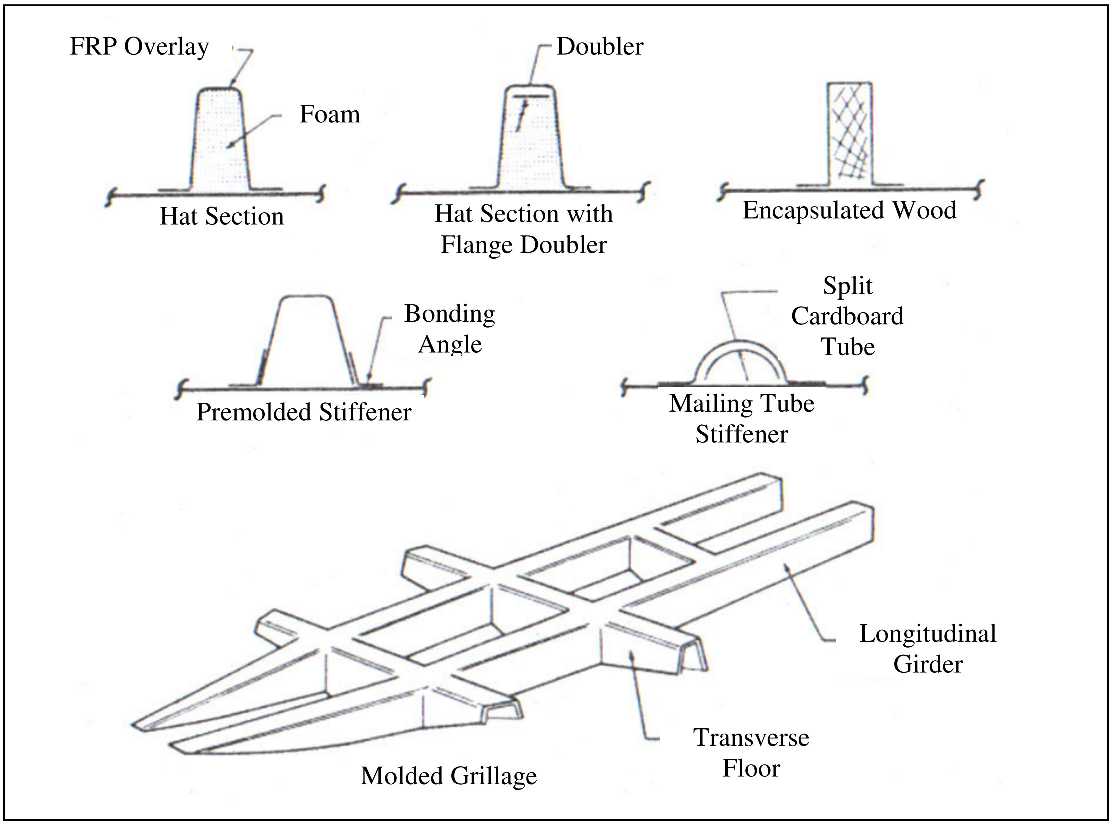


Figure 4.21. Typical framing members. (Scott 1996)

4. Premolded stiffener: This type offers the advantages of close control on dimensions for such critical areas as engine foundations and precludes the need for a core. Premolded stiffeners are generally installed with FRP boning angles which lap onto both the stiffener and skin.

5. Mailing tube: This is a variation on the hat section using a split mailing tube as a core. These stiffeners are less efficient than hat sections due to their geometry and are generally used only as panel stiffeners on lightly loaded structures.

6. Molded grillage: Several manufacturers of small powerboats have developed a molded structural grillage, incorporating both transverse and longitudinal members which is bonded to the hull with FRP bonding angels. The underside of the grillage is often foam-filled for flotation.

Framing members should be run continuously trough the structures, which support them, wherever possible, and should be rigidly bonded to the supports with small bonding angles. Where this is not possible the end connection should be carefully designed to minimize peel loads on the fiberglass laminates which transfer shear load from the stiffener to the support.

Bulkheads: The number and location of structural bulkheads provided in small boats is generally determined by arrangements rather than structural considerations. In small powerboats using outboard or inboard/outboard engines, bulkheads are seldom fitted. As the size grows and inboard engines are required, it is customary to provide forepeak and engine compartment bulkheads and, in larger sizes, additionally bulkheads are provided as arrangements permit. The hull receives additional support from lighter joiner bulkheads if they are well tied into the hull. If arrangements dictate a long span between structural bulkheads, perhaps 15 or 20 feet, it is desirable to provide an intermediate transverse floor to support bottom longitudinals unless they are very deep.

The number of structural bulkheads in a sailboat is critical due to the unique loading the hull encounters under full sail in heavy weather. Larger boats used in racing are now often fitted bulkheads or web frames on 8 to 10 foot centers.

Plywood is often used for bulkheads in FRP boats since it is relatively strong, rigid and inexpensive. They are normally not framed, except in very large boats, with required strength being provided by variations in thickness. The thickness of bulkheads may vary from about ½ inch in 20 to 30 foot boats up to a double layer of ¾ inch plywood in large fishing trawlers. Although this type of construction is heavier than the FRP sandwich panels, their cost is often an overriding consideration.

4.4.2. Sandwich Construction

The purpose of this construction is to increase the rigidity of a panel by increasing its thickness with relatively little increase in weight. This is achieved by use thin FRP skins bonded to a thicker, light weight core such as foam or balsa. Sandwich panels function similar to an I-beam, in that greater structural efficiency is achieved by placing the material further from the neutral axis. The skins resist bending while the core supports the load in compression and transfers it to the supports.

In the bending of sandwich panels a high sliding shear force is developed in the bond between the skin and core. The strength of this bond is extremely important to the performance of the panel. Without this bond the faces act independently, as indicated in Figure 4.22.(a). With this bond the faces and core work together, as shown in Figure 4.22.(b), increasing the strength and stiffness of the panel. For the loading shown in Figure 4.22.(b) the top skin is in compression and the bottom skin is in tension. The core is in compression directly under the load and over the supports and carries shear loads. There are tree basic core materials in general use. (see Figure 4.23.)

1. Those incorporating light weight cores of **foam or balsa**, in which the bending is resisted almost entirely by the skins, due to the very low modulus of the core.

2. These incorporating cores which are effective in bending, such as **plywood**, which has a modulus of elasticity similar to that of FRP. For this type the design of the panel must be based on the lower strength of the plywood.

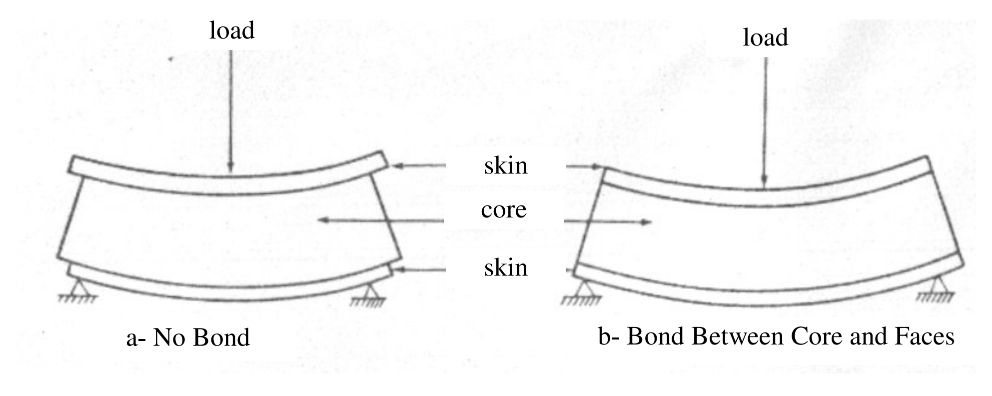


Figure 4.22. Interaction of core and faces. (Scott 1996)

3. Those incorporating thin **FRP webs** to separate the faces. This type of construction permits the use of thinner panels since the shear strength of the webs is far higher than that of foam or balsa. The voids between shear webs are generally filled with light density foam (2 pounds per cubic foot) both to provide a mold surface for layup of the web and to prevent their buckling.

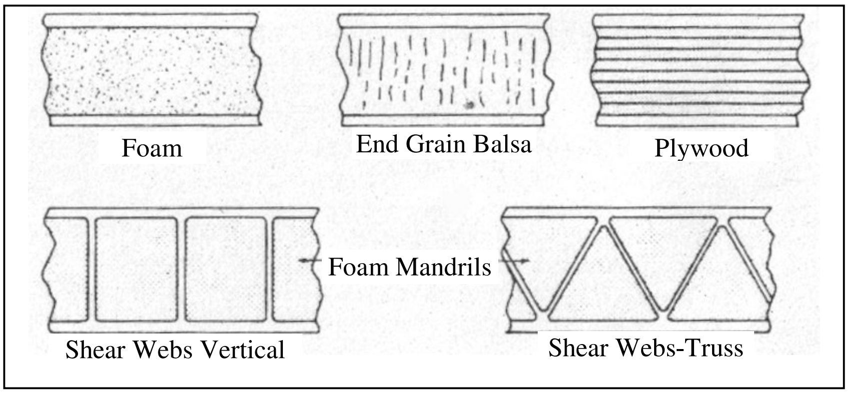


Figure 4.23. Typical core construction. (Scott 1996)

Construction with sandwich panels is more difficult than single skin because of the steps necessary to ensure a good bond between the skin and core. However, for equal stiffness, a sandwich panel will be both lighter and require less depth than a single skin with frames. Because of this sandwich construction is most commonly used for large flat surfaces such as decks, bulkheads, cabin tops and other areas where single skin construction would be either heavier or would result in a structure whose depth would infringe on headroom.

The stiffness of sandwich panels is particularly advantageous in constructing walking surfaces where the flexibility of thin single skin FRP panels would be unacceptable. Most people associated strength with stiffness and feel that a deck with “spring” or “sponginess” is weak. With fiberglass this is not necessarily, but the boatbuilding industry has had a accommodate this concern for deflection of decks by using either plywood or sandwich construction for walking surfaces as a preferable alternative to thicker single skins or uneconomically close frame spacing.

Because of the relatively low compressive strength of light-weight core materials it is necessary to provide higher strength core insert in way of through bolt or fittings. If the fitting loads are relatively light it is often possible to avoid core insert by providing large backing plates in way of the bolts. In way of through-hull fittings, it is preferable to taper the core away gradually and utilize single skin construction locally. This prevents possible soaking of the core and subsequent loss of bond strength.

The structural concepts mentioned above, are illustrated in **Appendix B**, which depict typical midship sections of a variety of FRP boats.

4.4.2.1. Cored Construction from Female Molds

Cored construction from female molds follows much the same procedure as that for single skin construction. The most critical phase of this operation, however, is the application of the core to the outer laminate. The difficulty stems from the following:

- Dissimilar materials are being bonded together;
- Core materials usually have some memory and resist insertion into concave molds;
- Bonding is a "blind" process once the core is in place;
- Contoured core material can produce voids as the material is bent into place; and
- Moisture contamination of surfaces.

Investigators have shown that mechanical properties can be severely degraded if voids are present within the sandwich structure. Most suppliers of contoured core material also supply a viscous bedding compound that is specially formulated to bond these cores. Where part geometry is nearly flat, non-contoured core material is preferable. In the case of PVC foams, preheating may be possible to allow the material to more easily conform to a surface with compound curves. Vacuum bag assistance is recommended to draw these cores down to the outer laminate and to pull resin up into the surface of the core.

4.4.2.2. Cored Construction over Male Plugs

When hulls are fabricated on a custom basis, boat builders usually do not go through the expense of building a female mold. Instead, a male plug is constructed, over which the core material is placed directly. Builders claim that a better laminate can be produced over a convex rather than a concave surface.

Figure 4.24. shows the various stages of one-off construction from a male plug. (A variation of the technique shown involves the fabrication of a plug finished to the same degree as described above under Mold Making. Here, the inner skin is laminated first while the hull is upside-down. This technique is more common with balsa core materials. A detail of the core and outer skin on and off of the mold is shown in Figure 4.25. With linear PVC foam, the core is attached to the battens of the plug with either nails from the outside or screws from the inside. If nails are used, they are pulled

through the foam after the outside laminate has cured. Screws can be reversed out from inside the mold.

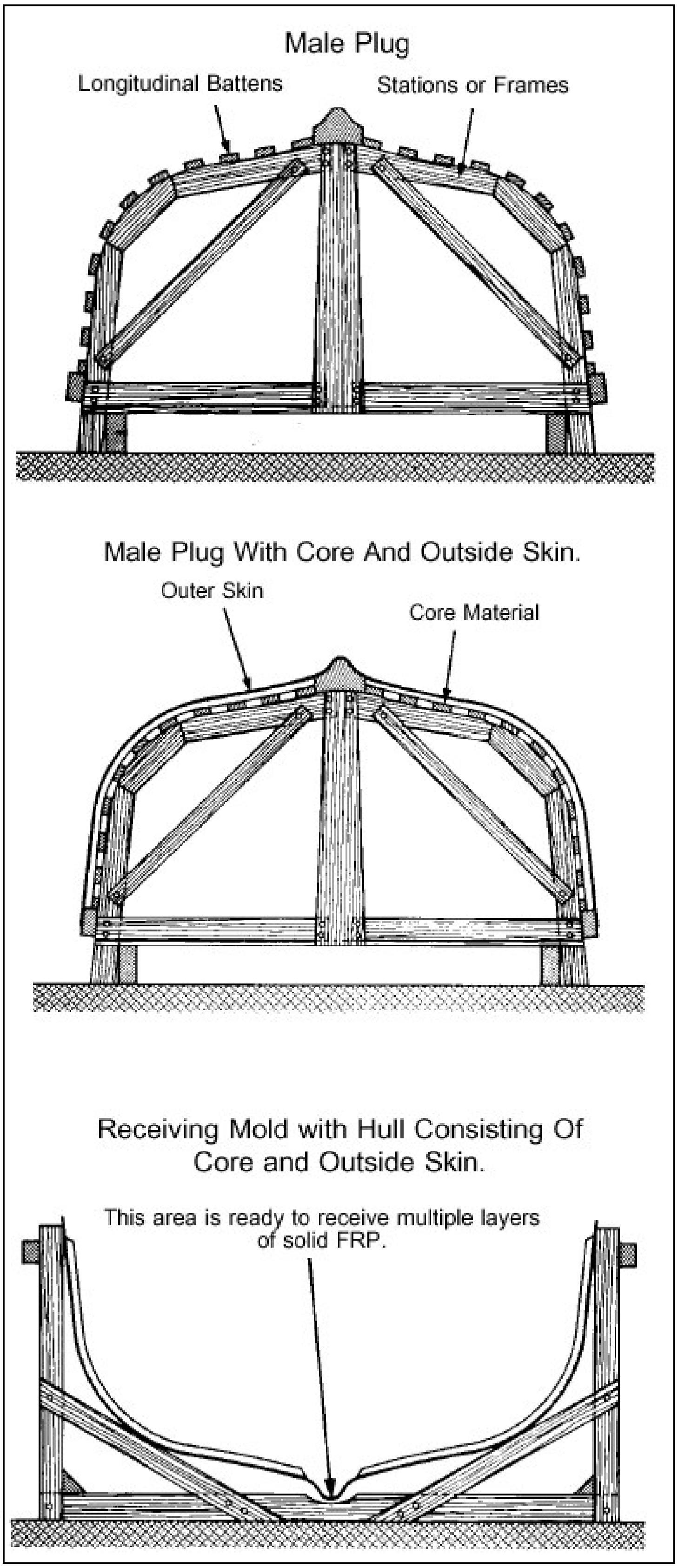


Figure 4.24. Simple, Wood Frame Male Plug used in Sandwich Construction (Greene 2004)

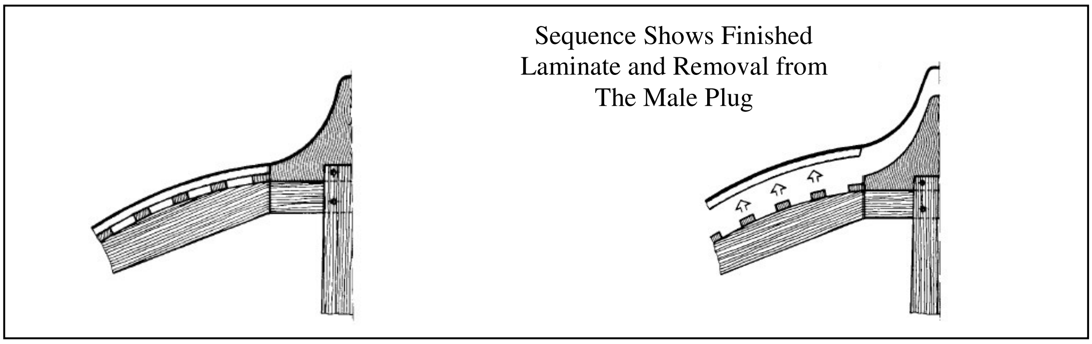


Figure 4.25. Detail of Sandwich Construction over Male Plug (Greene 2004)

4.5. Evolution of Recreational Boat Construction Techniques

From the 1950s to the 2000s, 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 4.26.

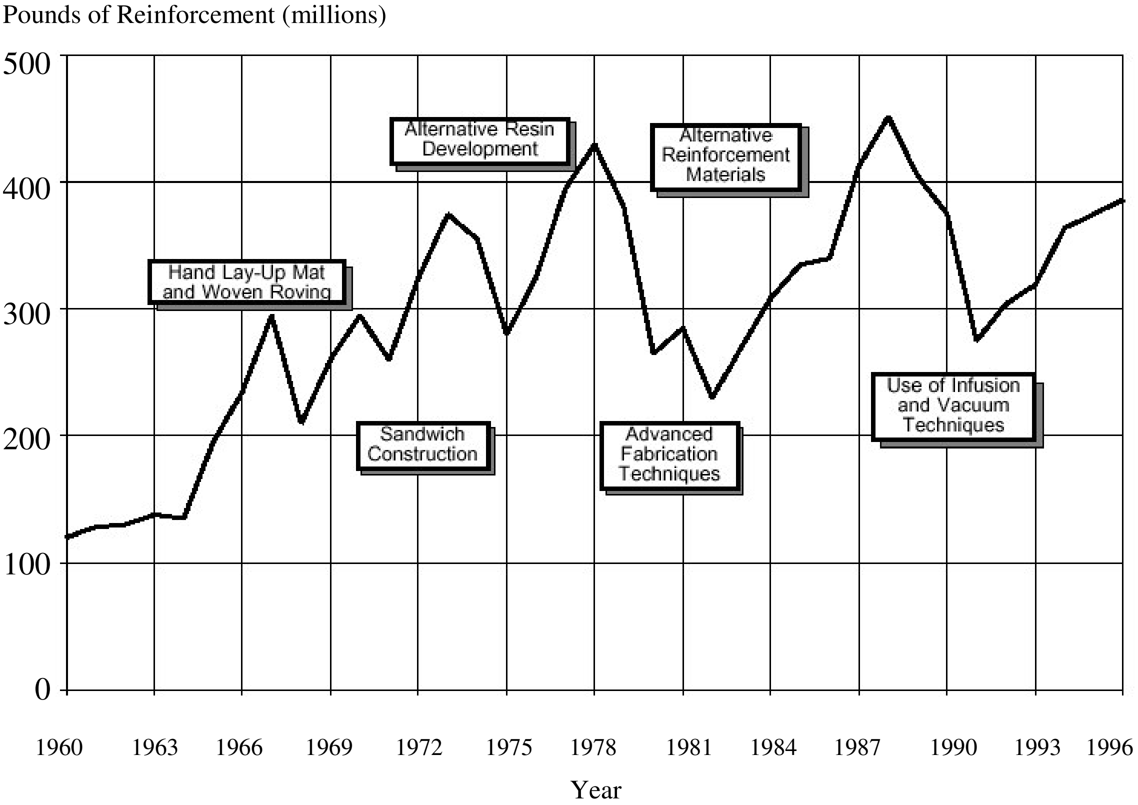


Figure 4.26. Annual Shipment of Reinforced Thermoset and Thermoplastic Resin Composites for the Marine Industry with Associated Construction Developments. (Greene 2004)

4.6. Recreational Boat Construction Techniques

There are various fabrication processes applicable to marine composite structures such as hand lay up, spray up, compression molding, filament winding, pultrusion, vacuum bag molding, autoclave molding and resin transfer molding. The most common technique used for large structures such as boat hulls, is the open mold process. Specifically, hand lay-up or spray-up techniques are used. Spray-up of chopped fibers is generally limited to smaller hulls and parts.

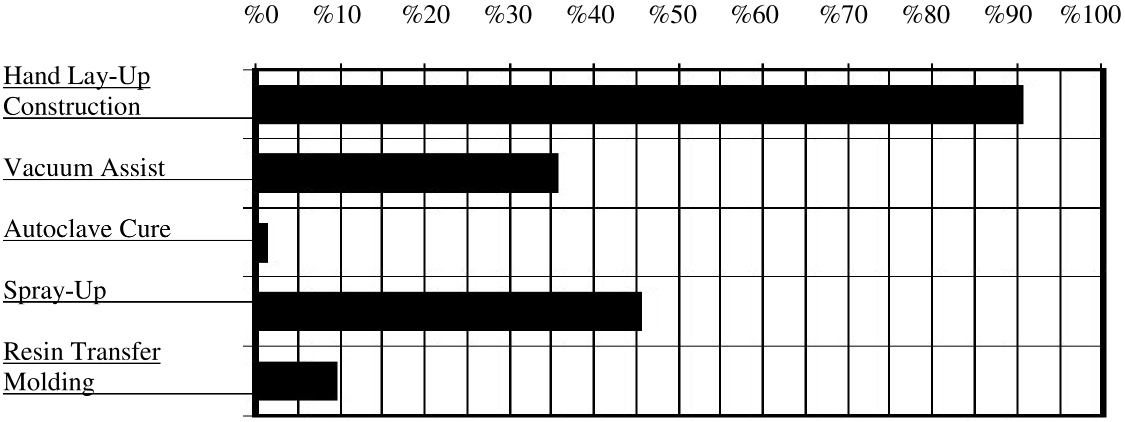


Figure 4.27. Building Processes (Greene 2004)

4.6.1. Open molding

Open molding is the most common method in marine production process used to fabricate composites parts accounting for over 40% of composites processed world-wide. It is a relatively simple process with low investment cost but a high degree of manual handling. Virtually all types of reinforcement can been used in open molding which together with the use of core materials to create sandwich structures enables access to the widest range of mechanical and structural performance of any composites process. Unsaturated polyester resins dominate in this area but epoxy and vinyl ester resins are also common. Open molding can be used for a very wide range of moldings from caravan parts and cladding panels to boat hulls and radomes. Typical economic run lengths range from 2 or 3 individual parts up to several hundred.

4.6.1.1. Hand Lamination

The process starts with the construction of a mould. The mould is most commonly constructed from composites material using a model made from wood, plaster or any other suitable modeling material. Only one, normally female, mould half is needed which defines the exterior surface of the part. Most often the first stage of molding is to brush or spray a polymer coating or gel coat onto the mould surface. Gel coats are available in a wide range of different colors and effects and are selected to protect the part from environmental degradation or chemical attack and provide the desired aesthetics.

After the gel coat has been allowed to cure fiber reinforcement in sheet form is laid in place in the mould. Glass fiber is the most common reinforcement in the form of chopped strand mat but other fibers such as carbon or aramid may be used. A very wide range of reinforcement types are available and can be positioned and oriented in the mould giving the ability to vary the mechanical performance across the part. The design of the glass fiber pack is a key to the performance of the composite part and the ability to change it at will gives great flexibility to the hand lay process.

The next stage of the process is to pour liquid catalyzed resin over the reinforcement and to work it into the reinforcement using rollers. This process is very labour intensive but extremely important as it ensures even distribution of the resin, full impregnation and wetting out of the reinforcement and removal of air. Unless the process is carried out effectively the composite part will not perform correctly. Further layers of reinforcement and resin are applied according to the requirements of the part and core materials such as rigid foam, balsa wood or honeycomb may be included to create sandwich structures.

When the lay up is complete the molding is left to cure. This normally occurs at ambient temperature and can take anything up to 10 hours. The molding is then released from the mould and trimmed to remove excess material from the edges of the molding. Sometimes moldings are cured at slightly elevated temperatures to improve speed and productivity and may also be post cured at even higher temperatures to achieve the maximum performance.

4.6.1.2. Spray Lamination

Spray lamination is very similar to hand lay-up apart from the method of placing the reinforcement and the resin into the mould. Rather than using reinforcement in the form of mat, resin and reinforcement are co-sprayed into the mould using a combined resin spray and chopper gun.

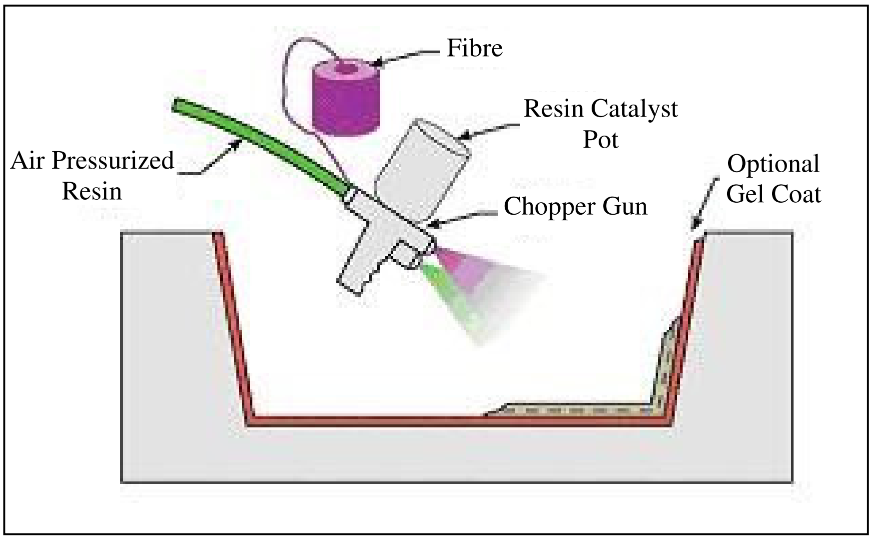


Figure 4.28. Spray Lamination. WEB_9 (2004)

This process is much easier and faster than hand lay-up and can be automated using robotized spray guns. This does eliminate much of the manual labor involved in positioning the reinforcement in the mould and will result in higher productivity although rolling is still necessary to ensure proper consolidation of the part. Spray lamination can be used in combination with hand lay where different types of fiber or constructions are required to achieve specific properties.

4.6.2. Closed molding

Closed molding is the name given to fabrication techniques in which reinforced plastic parts are produced between the halves of a two-part mold or between a mold and a flexible membrane, such as a bag. There are four types of closed molding methods that are being used in boat manufacturing operations: vacuum bagging, vacuum-assisted resin transfer molding, resin transfer molding, and compression molding with sheet molding compound.

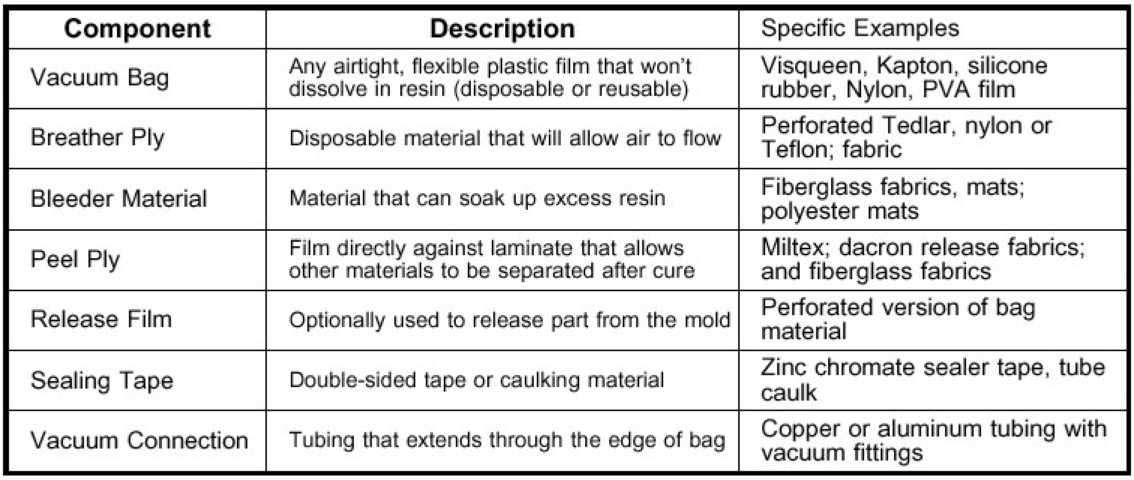
4.6.2.1. Vacuum Bagging

An increasing number of builders are using vacuum bag techniques to produce custom and production parts. By applying a vacuum over a laminate, consolidation of reinforcement materials can be accomplished on a consistent basis. A vacuum pressure of 14.7 psi is over a ton per square-foot, which is much more pressure than can reasonably be applied with weights. (Marshall 1993, Greene 2004). As with most advanced construction boat building practices, specialized training is required and techniques specific to the marine industry have evolved.

Vacuum bagging is a partially closed molding technology. It uses techniques similar to open molding but with a modification in the resin curing stage. After resin has been applied (either by hand lay-up or spray lay-up), a flexible, clear plastic sheet is placed over the wet laminate and sealed along the edge of the mold to form a "bag." A porous material called a bleeder sheet is also placed under the bag and a hose connected to a vacuum pump is sealed under the edge of the bag. The vacuum pump is used to draw the air out from under the bag and press the bag down onto the part. The pressure of the vacuum removes any trapped air and excess resin from the part and presses the layers of laminated material together. This technique is used to increase the fiber-to-resin ratio, which generally increases the strength of a part, and also to obtain a good bond between FRP skins and non-FRP core materials, such as wood or foam. Core materials are often sandwiched between layers of FRP to make a thicker and stiffer part without significantly increasing the part's weight.

The most common use of vacuum bagging in marine construction is for bonding cores to cured laminates. This is called “dry-bagging,” as the final material is not wet-out with resin. When laminates are done under vacuum, it is called “wet-bagging,” as the vacuum lines will draw directly against reinforcements that have been wet-out with resin. For wet-bagging, a peel-ply and some means for trapping excess resin before it reaches the vacuum pump is required. (Lazarus 1994)

Table 4.1. and Figure 4.29. list some materials used in the vacuum bag process.



Component	Description	Specific Examples
Vacuum Bag	Any airtight, flexible plastic film that won't dissolve in resin (disposable or reusable)	Visqueen, Kapton, silicone rubber, Nylon, PVA film
Breather Ply	Disposable material that will allow air to flow	Perforated Tedlar, nylon or Teflon; fabric
Bleeder Material	Material that can soak up excess resin	Fiberglass fabrics, mats; polyester mats
Peel Ply	Film directly against laminate that allows other materials to be separated after cure	Miltex; dacron release fabrics; and fiberglass fabrics
Release Film	Optionally used to release part from the mold	Perforated version of bag material
Sealing Tape	Double-sided tape or caulking material	Zinc chromate sealer tape, tube caulk
Vacuum Connection	Tubing that extends through the edge of bag	Copper or aluminum tubing with vacuum fittings

Table 4.1. Materials Used for Vacuum Bagging. (Greene 2004)

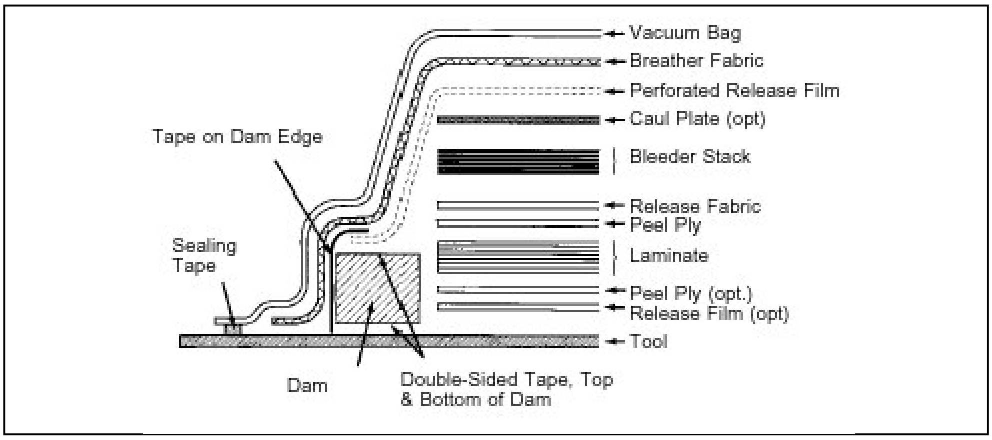


Figure 4.29. Vacuum Bag Materials for Complex Part. (Greene 2004)

Figure 4.30. Sealing Tape is applied to Mold Prior to Vacuum Bag Use (Greene 2004)

Vacuum bagging offers the following advantages over conventional open molding:

- Minimized worker exposure to styrene curing emissions;
- Stronger and lighter parts with less voids and higher glass to resin ratios;

- Better bonding between FRP skins and non-FRP core materials; and
- Reduced labor and rolling equipment needs because rolling to remove air bubbles and excess resin is not needed.

Figure 4.31. Overhead High- and Low-Pressure Vacuum Lines. (Greene 2004)

4.6.2.2. Vacuum-Assisted Resin Transfer Molding

Vacuum-Assisted Resin Transfer Molding (VARTM) is a closed molding technology that uses a vacuum to pull resin into dry fiberglass reinforcements that are placed into a closed mold. The closed mold may be formed using a flexible plastic sheet or "bag" as in vacuum bagging, or by a rigid or semi-rigid cover that matches the shape of the mold. In all variations, the bag or cover is sealed to the mold and vacuum pressure is used to draw resin from an outside reservoir into the sealed mold through a system of distribution tubes and channels placed under the bag or cover.

One VARTM process that has been used by several boat manufacturers is a patented technology called the Seeman Composites Resin Infusion Molding Process (SCRIMP) which is licensed by SCRIMP Systems, LLC.

Figure 4.32. Dry Reinforcement In-Place for SCRIMP Process (Greene 2004)

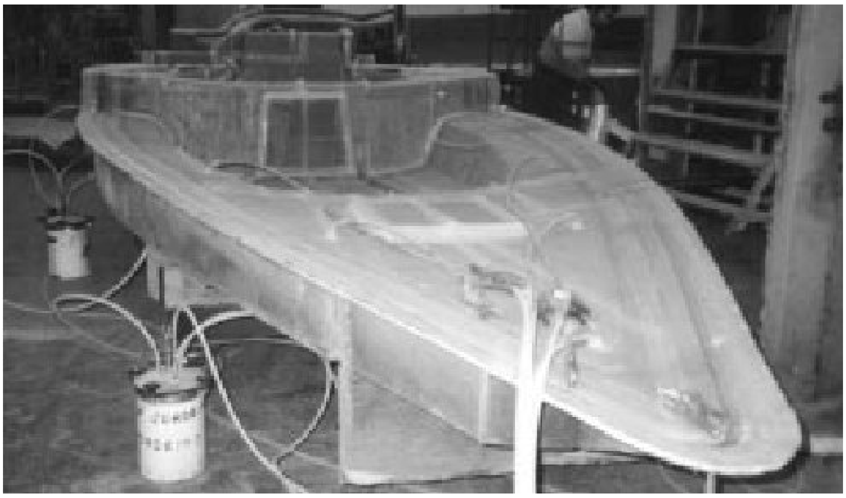


Figure 4.33. SCRIMP Infusion Arrangement (Greene 2004)

In the SCRIMP process, the mold is coated with a gel coat finish and a skin coat is applied using conventional techniques. Dry reinforcements and core materials are then placed in the mold. The resin distribution system and the bag are then placed over the mold and sealed to the edge of the mold. The vacuum is then applied to pull the bag against the mold and the reinforcements and the bag is checked for leaks. Valves to the resin supply system are then opened and the resin is pulled into the reinforcements by the vacuum. When the reinforcements are thoroughly saturated with resin, the resin supply is shut off and the part is allowed to cure under a vacuum. After curing, the bag is removed and is either discarded or reused, depending on the material from which it is made. Disposable bags are made from plastic film, whereas reusable bags are made from silicone rubber. A silicone bag can be used for more than 500 parts.

Figure 4.34. SCRIMP U.S. Coast Guard Motor Lifeboat Built by OTECH. (Greene 2004)

The SCRIMP process has been used by one manufacturer (TPI Composites, Inc.) to build small (13 foot) sailboats and large sailboats up to 90 feet. TPI builds about 400 boats per year using SCRIMP and also uses the process to manufacture other reinforced plastic parts, including windmill blades and exercise pools. Several other smaller boat manufacturers that are not major HAP sources are also using the process to build both power and sail boats of a variety of sizes including motor surf lifeboats for the U.S. Coast Guard.

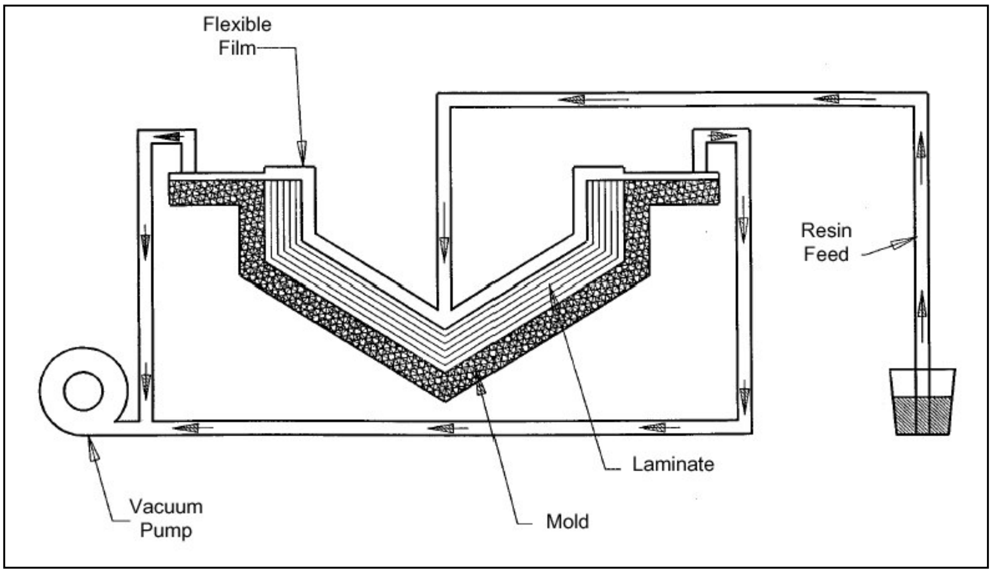


Figure 4.35. Schematic of SCRIMP Process. (Greene 2004)

The VARTM process has the following advantages over conventional open molding:

- Minimizes worker exposure to resin and styrene; this makes for a cleaner and more comfortable work environment and reduces the need for personal protective equipment such as respirators, gloves, and coveralls;
- Reduces the need for ventilation make-up air (and associated electrical and heating costs) to maintain styrene concentrations within acceptable exposure levels;
- Reduces the labor needed to apply resin and perform detail rolling of the laminate;
- Reduces the need for clean-up solvents for resin application equipment;
- Reduces the need for resin application equipment (e.g., spray guns, pumps, and detail rollers) and associated maintenance costs;
- Produces parts with a higher glass-to-resin ratio and fewer voids, which generally results in stronger and more durable parts;
- Can produce lighter parts if a core material is incorporated into the laminate in place of some of the fiberglass; and
- Produces more consistent parts because the fiberglass reinforcements are placed into the mold dry and can be precisely located before resin is applied and because resin application is more controlled and predictable.

4.6.2.3. Resin Transfer Molding

Resin transfer molding (RTM) uses two rigid mold halves to provide the shape for fabrication of FRP boat parts. In a typical resin transfer molding (RTM) operation, gel coat is spray applied to the inside surface of both halves of the mold so that the part has two finished sides, instead of one as in open molding. After the gel coat cures, the dry reinforcement is laid inside the mold and the mold is closed with clamps. When closed, the two halves of the mold mate together with a narrow space between them equal to the thickness of the finished part. Catalyzed resin is injected into the closed mold where it saturates the fiberglass. While the part is still in the mold, the resin cures. After the resin has cured, the mold is opened and the finished part is removed.

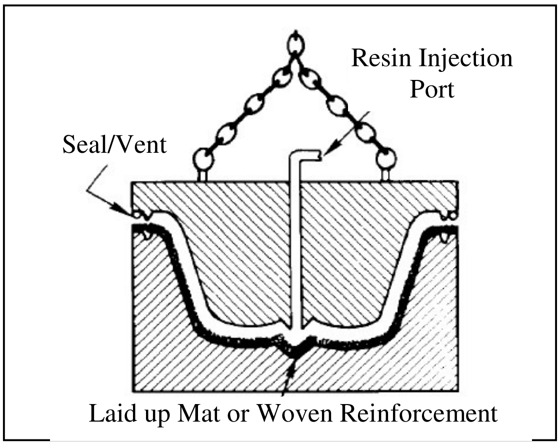


Figure 4.36. Resin transfer molding. (Greene 2004)

The RTM process is most economical for making many copies of small parts, especially when a smooth finish is desired on both sides of the part. Typical applications of RTM in boat manufacturing are for making hatch covers, doors, and seats.

The RTM process has several advantages compared to conventional open molding :

- RTM is more economical than open molding for producing many copies of relatively small parts such as hatch covers and seats because of reduced labor during resin application; the use of pre-formed fiberglass reinforcements can add to these labor savings;
- Minimizes worker exposure to resin and styrene; this makes for a cleaner and more comfortable work environment and reduces the need for personal protective equipment such as respirators, gloves, and coveralls;
- Reduces the need for clean-up solvents for resin application equipment;
- RTM produces more consistent parts than open molding; C RTM can produce parts with two smooth finished sides; and
- Parts can be produced more quickly with RTM because the heat of injecting the resin accelerates the resin curing and allows for faster mold cycle times.

4.6.2.4. Compression Molding using Sheet Molding Compound

Compression molding involves the use of a prepared compound such as sheet molding compound (SMC) and a large hydraulic press to produce FRP parts. The prepared SMC sheet is composed of resin and fiberglass fibers. To create a FRP part with compression molding, SMC sheets are cut to the proper size and put into a matched male and female mold. The two molds are pressed together in the hydraulic press under several tons of pressure. The SMC is forced into all areas of the mold and cures in the closed mold under high heat and pressure in a matter of minutes. Several facilities are currently using compression molding with SMC to produce hulls, decks, and other parts for PWC. These facilities are producing parts on the order of tens of thousands per year.

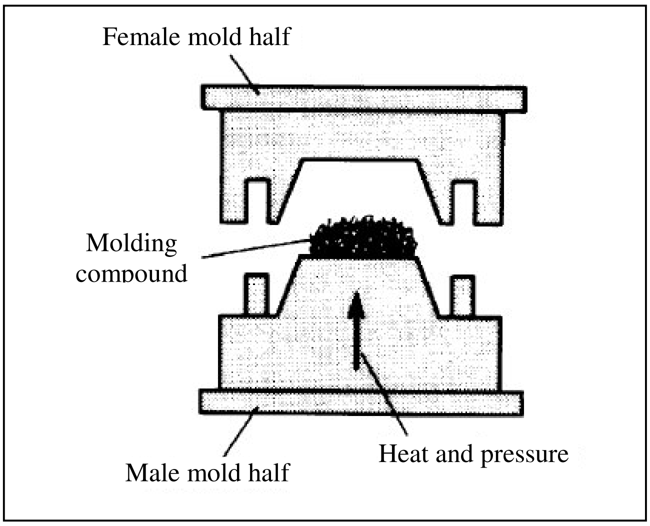


Figure 4.37. Compression molding. (Greene 2004)

The compression molding process with SMC has the following advantages compared to other molding technologies:

- The rapid curing of the parts under high heat and pressure permits rapid mold cycle times and high production volumes;
- The automated process and the use of SMC reduces labor costs compared to open molding; and
- Minimizes worker exposure to resin and styrene; this makes for a cleaner and more comfortable work environment and reduces the need for personal protective equipment such as respirators, gloves, and coveralls;

- Reduces the need for clean-up solvents for resin application equipment; and
- There is no need to apply gel coat to the mold prior to molding.

4.7. Future Trends for FRP Boat Construction

Prepregs: The term prepreg is short for pre-impregnated material and refers to reinforcements that already contains resin and are ready to be placed in a mold. The resin (usually epoxy) is partially cured to a “B-stage,” which gives it a tacky consistency. Prepreg material must be stored in freezers prior to use and require elevated temperatures for curing. Aerospace grade prepregs also require elevated pressures achieved with an autoclave for consolidation during curing.

A lot of builder use prepregs for the construction of lightweight, fast vessels. Notable applications include America's Cup sailboats and hydroplanes racing on the professional circuit. Because marine structures are quite large, curing is typically limited to oven-assisted only, without the use autoclaves. Some marine hardware and masts are made using conventional aerospace techniques.

Figure 4.38. Prepreg Material is positioned in Mold (Greene 2004)

Figure 4.39. Prepreg Material is consolidated solidated in Mold (Greene 2004)

Prepregs are classed by the temperature at which they cure. High performance, aerospace prepregs cure at 350°F or higher and commercial prepregs cure at 250°F.

A new class of "low energy cure" prepregs is emerging, with cure temperatures in the 140°F to 220°F range. These materials are particularly suited to marine construction, as curing ovens are typically temporary structures. (Juska et al. 1996) Eric Goetz used this method to build all of the 1995 America's Cup defenders.

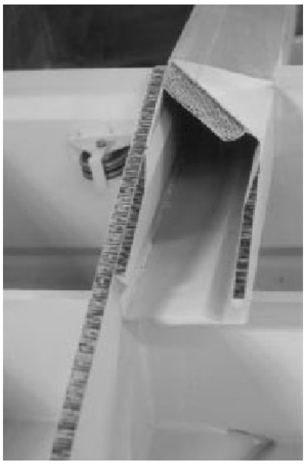


Figure 4.40. Deck Beam Construction (Greene 2004)

Figure 4.41. Hydroplane Hull and Cockpit Assemblies at Ron Jones Marine (Greene 2004)

Builders such as Goetz and Ron Jones who have developed techniques for fabricating marine structures with prepregs are hesitant to go back to wet lay-up methods. They cite no styrene emission, ease of handling, increased working times and higher part quality and consistency as distinct advantages. On the down side, prepreg material costs about four times as much as standard resin and reinforcement products; requires freezer storage; and must be cured in an oven. As reduced VOC requirements force builders to look for alternative construction methods, it is expected that demand will drive more prepreg manufacturers towards the development of products specifically for the marine industry.

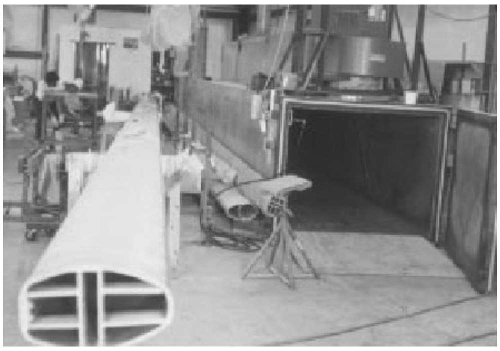


Figure 4.42. Cure Oven Used for Masts and Hardware at Goetz Marine Technology (Greene 2004)

Thick Section Prepregs: Composite Ships, Inc. of Arlington, VA is developing a prepreg process based on DSM, Italia materials that may lead to the construction of large, thick marine structures. With promising compressive strengths near 70 ksi, material costs over $5/lb are expected to be offset by the need for fewer plies and ease of fabrication.

Figure 4.43. Prepreg Ply of E-Glass is Rolled Out on Consolidation Table (Greene 2004)

Figure 4.43. shows unidirectional prepreg being laid out on a preparation table. Successive plies of 0° or ±45° E-glass/epoxy are consolidated in bundles of six, with a one inch offset to create a lap joint edge. The bundled group of plies is then passed through a consolidating "wringer," as shown in Figure 4.44. (Greene 2004)

Figure 4.44. Prepreg "Bundle" of Six Layers of Unidirectional E-Glass is Passed Through Consoli-dator for a Stiffener by Composite Ships (Greene 2004)

The "tacky" bundle is then placed in a metal mold and "smoothed" in place. Hand consolidation with plastic putty knives to remove trapped air is assisted by the addition of some base resin, which is a B-stage epoxy.

For components such as stiffeners, the prepreg can be semi-cured at 120°F on a wood mold to create a stiff form to work with. The component is then bonded to the hull with a resin putty.

The prepreg is stored at 0°F and warmed to room temperature for one hour before use. After stabilization in the mold, the material can stay at a stabilized state for several months before the structure is cured. An entire hull structure, including semi-cured internals, is then cured in an oven built using house insulation materials. Heat is also applied to the steel mold via thermocouple feedback control. Full cure requires a temperature of 185°F for 24 hours. The U.S. Navy has sponsored the production of a half-scale Corvette midship hull section to validate the process for large ship structures.

Thermoplastic-Thermoset Hybrid Process: A company called Advance USA is currently constructing a 15 foot racing sailboat called the JY-15 using a combination of vacuum forming, injection foam and resin transfer molding. Designed by Johnstone Yachts, Inc. the boat is a very high-performance planing boat.

The hull is essentially a three-element composite, consisting of a laminated thermoplastic sheet on the outside, a polyurethane foam core and an inner skin of RTM produced, reinforced polyester. The 0.156 inch outer sheet is vacuum formed and consists of pigmented Rovel ® (a weatherable rubber-styrene copolymer made by Dow Chemical and used for hot tubs, among other things) covered with a scratch resistant acrylic film and backed by an impact grade of Dow's Magnum ABS. The foam core is a two part urethane that finishes out to be about three pounds per cubic foot. The inner skin is either glass cloth or mat combined with polyester resin using an RTM process.

The hull and deck are built separately and bonded together with epoxy as shown in Figure 4.45. Although investment in the aluminum-filled, epoxy molds is significant, the builder claims that a lighter and stronger boat can be built by this process in two-thirds the time required for spray-up construction. Additionally, the hull has the advantage of a thermoplastic exterior that is proven to be more impact resistant than FRP. Closed-mold processes also produce less volatile emissions. (Miller 1989)

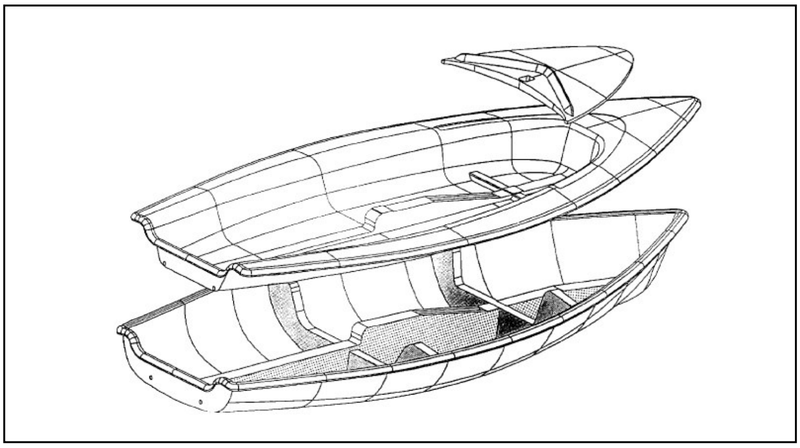


Figure 4.45. Schematic of JY-15 Showing Hull and Deck Parts prior to Joining with Epoxy (Greene 2004)

Preform Structurals: Compsys of Melbourne, FL has developed a system for prefabricating stringer systems of various geometries for production craft that contain all dry reinforcement and core material. Prisma preform systems feature a dry fiber-reinforced outer surface that is cast to shape with a two-part, self-rising urethane foam core. Sufficient reinforcement extends beyond the stringers to permit efficient tabbing to the primary hull structure.

Preform stringer and bulkhead anchor systems are delivered to boat builders, where they are set in place and coated with resin simultaneously with the primary hull structure. Compsys claims that builders realize significant labor savings and improved part strength and consistency.

Figure 4.46. Two-Part Expansion Foam is Injected into Stringer Molds at Compsys with Careful Monitoring of Material Flow rate and Duration (Greene 2004)

UV-Cured Resin: Ultra violet (UV) cured resin technology, developed by BASF AG, has been available in Europe for the past 10 years, and is being promoted in the U.S. by the Sunrez tm Corporation of El Cajun, CA. The technology promises long pot life and rapid curing of polyester and vinyl ester laminates.

BASF developed a light initiator for rapid curing of polyester and vinyl ester resins at their laboratories in West Germany ten year ago. Total cure times of 3 minutes are typical for parts of 3/16" and under 10 minutes for parts 1/2" thick, using open molds and hand or machine application of the resin and glass. Sunrez tm also claims that styrene emissions can be reduced by up to 95% depending on the fabrication method used. (This is based on a fabrication process patented by Sunrez tm).

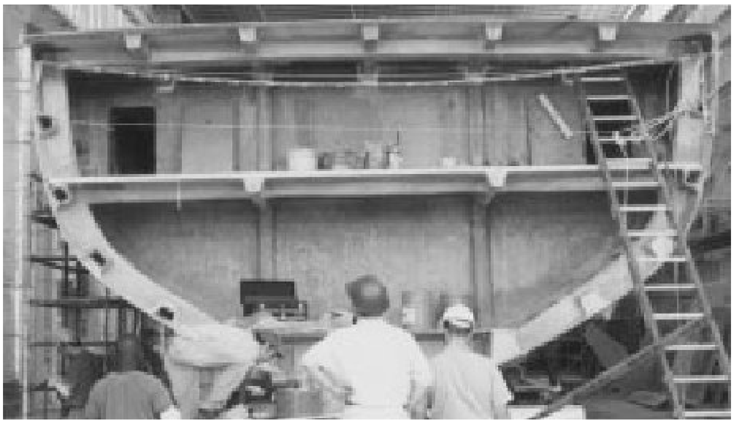


Figure 4.47. One-Half Scale Corvette Hull Test Section Built for the U.S. Navy Using the Sunrez Process (Greene 2004)

A BASF photo-initiator is added to a specially formulated version of a fabricator's resin and is shipped in drums or tanker to the shop. The resin is drawn off and used without the addition of a catalyst. The part is laminated normally and any excess resin is saved for the next part.

When the laminator feels that he has completed the laminate, the part is exposed to UV light, and cured in 3 to 5 minutes. (Greene 2004)

CNC (Computer Numerical Control) Design Automation: “Today’s robotics give boat builders a range of tooling options nor available just ten years ago.” (Harp 2001) Recent innovations in hardware and software have opened new horizons in the way technology used in boat building industry. One of them is CNC milling in boat production. The goal in CNC milling is to be able to cut the plug automatically without any lengthy final preparation by hand. A variety of materials can be machined by CNC, including foam, wood, plastic and fiberglass compounds.

Machined tooling for FRP boats can take variety of forms such as From CNC-cut frames for manually constructed plugs, to limited production female tools, to CNS-cut plugs over which production female molds are laminated.

- **CNC Milling**

A milling machine is a machine tool that removes material from a work piece by rotating a cutter and moving it into the material. CNC design automation consists of five stages. These are concept stage, design stage, model stage, milling stage and molding stage.

Firstly a concept study project is prepared and then 3D model is made for CNC from this concept study. (Figure 4.48.) After 3D model, milling stage can start. (Figure 4.50. – Figure 4.41.). By the finish of milling process, molding process start in which the final mold is produced. (Figure 4.52. - figure 4.53.)

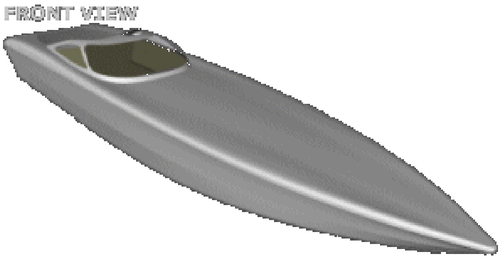


Figure 4.48. 3D model of a boat
WEB_19 (2004)

Figure 4.49. Finish Project of race boat
WEB_19 (2004)

Figure 4.50. CNC milling for hull
WEB_19 (2004)

Figure 4.51. Cockpit. WEB_19 (2004)

Figure 4.52. Molding process. WEB_19 (2004)

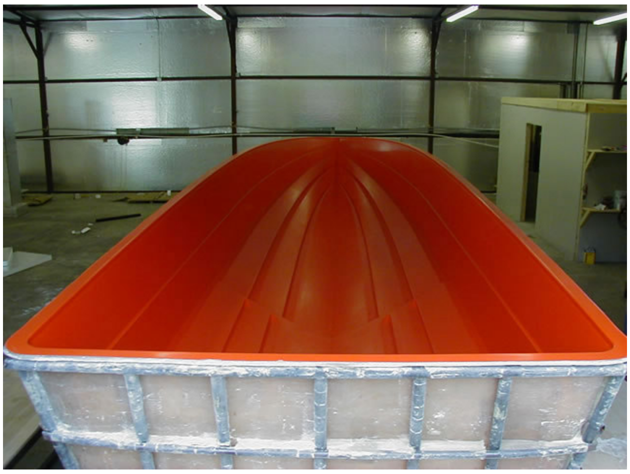


Figure 4.53.Final mold. WEB_19 (2004)

- **Summary of CNC Milling Process**

1. Design the boat using some form of CAD hull or surface design program.
2. Write a transfer geometry file (DXF, IGES, etc.) of the hull
3. Read the geometry file into the CAM program
4. Adapt or correct the geometry to meet the needs of the CAM software
5. Define the cutter tool paths over the surfaces using the CAM software
6. Break the job into pieces that will fit on the machine
7. Mill the individual pieces
8. Drill the connection pin locations or alignment marks for the milled parts
9. Prepare the plug for use or use it to create the final mold

4.8. Investigation on production of Gulets

There is a lot of gulet definition related to length, hull form and rigs of gulet. The authoritative definition of gulet is: " A two-masted, lightly rigged sailing vessel, smaller than a brig, with a fully rigged foremast with square sails and the mainmast with gaff-rigged mainsail." WEB_5 (2004)

However, contemporary usage amongst the Turkish sailing community differs. A gulet is a two-masted, ketch or schooner-rigged steel or wooden yacht with widely varying sail plans and characterized by a wide, rounded stern.

Figure 4.54. View of a Gulet. WEB_5 (2004)

A boat has to be constructed strong enough against to environmental loads, suitable to international rules and has to be comfortable. When these required conditions are provided, boats are going to be preferred in local and international areas whatever its material and production method.

Figure 4.55. View of a Gulet's stern. (Gölpınar 2004)

4.8.1. Production Materials and Methods of Gulet

There are two-type material used in production of gulet such as wood and steel. Steel gulets' market is restricted because of the people's demand, which towards to natural yacht with wood. There is only a firm that produce steel gulet called Ege-Yat.

They prefer this material because of its low cost, low material waste and the low production time when compared to wooden gulets. But the consumer's demand is still toward to wooden gulets because of its comfort, natural aesthetic and natural thermal insulation. With the development in modern glues and application methods, usage of wood gains importance again for production of boats.

Conventional wooden boats must be built with suitable process trees. However, modern glues (epoxy resins) have been useable for boat manufacturers. Wooden boat technology has two new methods.

Monocoque wooden boat building method: This technology is being used especially in Europe, USA and Australia. Wooden boats are built by lamination method completely.

Hybrid wooden boat building method: This technology is being preferred because of investment cost is less than investment cost of monocoque wooden boat and structural strength is higher than structural strength of conventional wooden boat. In this method, boat's parts that are keel, stem and frame are built by lamination method.

In hybrid wooden boat building method is used both conventional and laminated wooden boat building methods.

4.8.1.1. Conventional Wooden Boat Building Method

This method is cheaper than the laminated wooden boat building method. But, it has low strength against to dynamic and static loads. Gaps on board are caulked. After this application, it occurs a lot of problems on boat, especially on underwater surfaces. In this method, wood parts are fixed with nails and nuts. Because of temperature and moisture ratio variation, fixed parts leave from each other in the future. So, repairing of these boats is both harder and more expensive than repairing of laminated wooden boats. Repairing works of these boats are cleaning and removing paint on board. Then, the boat is repainted. However, it must be recaulked about one times at 5 years. All these repairing works can be done about 3 months after they were carried marina.

Figure 4.56. View of a maintaining Gulet. (Gölpınar 2004)

Generally, naval architect isn't worked in yards where is built conventional wooden boat. Boat builders don't think about using new technologies and engineering services. They are contented with old methods in this building. So, it is used excessive wooden material for building that the boats become heavy. This occurs to selected stronger engine. Thus, maintenance costs also increase. It is necessary to select correct wooden material for hull form in this method. So, it takes a lot of times. After collection, all collected materials are spread and then the most suitable are selected by model. It's necessary to have a wide area and long working time to operate. Hierarchy of wooden boat building was listed below:

1. Ballast is seated on launching way after ballast was prepared by sheet iron. The ballast decreases the center of gravity of boat and supports wooden keel. Because of decreasing the center of gravity becomes stable the boat.

2. Keel is seated on the ballast after it was prepared. The keel can be prepared from adding wooden each other. Stem post and stern are prepared and seated on the keel. It is prepared keelson for seating floors on the keel.

3. Preparing floors. If it couldn't be found suitable tree form for a floor, it is prepared as an adding frame. Then, two similar frames (sister frames) are seated side by side on keelson for obtaining enough structural strength by floors. While the frames are being preparing, woods are diminished about 50%.

4. After the inside keel is prepared; it is seated on the keelson and fixed on the keel by galvanized nuts.

5. Stringers are fixed frames after they were prepared. Stem is strengthened against to effects that will come from sea. Beams, carlins and puntels were prepared. Board is covered by carved planks and fixed on frames by nails.

6. Deck is covered and cabins are built. Tanks and engine beds are prepared.

7. Equipment is seated. After board was cover, it is caulked. Then, it is puttied and painted.

Figure 4.57. Wooden Framework of a Gulet. (Gölpınar 2004)

4.8.1.2. Laminated Wooden Boat Building Method

Although wood is a suitable material for boat building, it can decay and burn easily. Today, these problems of wood can be solved by wood lamination method. It's a process that glue (epoxy resin) is injected into the wood to protect harmful organisms (fungus, insects, etc.). Epoxy resins also are used to protect the wood against the moisture in this method. All surfaces covered by epoxy resin don't let to penetration of moisture into the wood. So, strength of wood doesn't change. Properties and advantages of epoxy resins were listed below:

1. They are fluent materials. So, they penetrate into the wood easily.

2. Their shrinkage coefficient is low. So, tension does not occur between epoxy resins and the other filling materials.

3. They protect wood surfaces against to environmental effects and chemical materials.

4. It's easy to use epoxy resins with other filling materials. After using them, it does not occur any cracking and removing on the surface.

5. They increase the wooden life. However, wood diminution is about 10% in laminated wooden boat building method. So, wood consumption decreases.

6. Laminated wood materials have more advantage than the other boat building materials.

7. When moisture ratio in wood cells increases, strength of wood decreases. For example, strength of a wood having 17% moisture ratio is 6% higher than the strength of wood having 30% moisture ratio. So, in wooden boats, especially on board and underwater surface, have to be used epoxy resins for protecting.

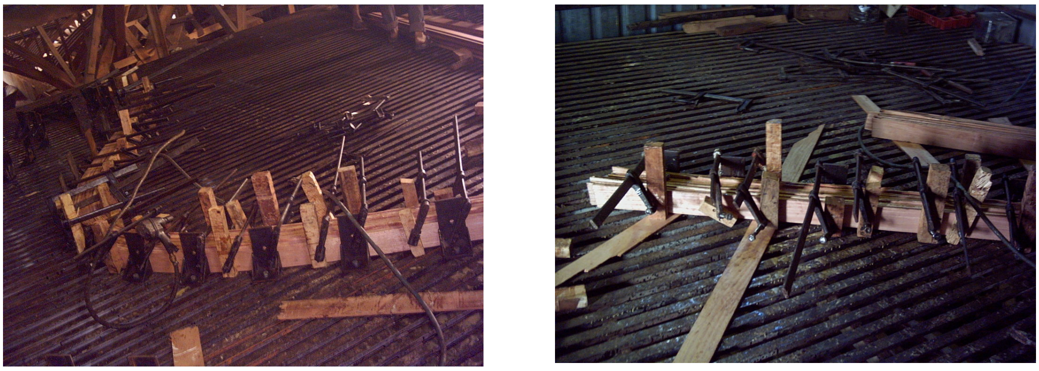


Figure 4.58. Laminating views of a keel. (Gölpınar 2004)

There are some important points to use epoxy resins. Before using epoxy resin, it should be taken information from epoxy resins manufacturers and experts and cost analysing should be performed. Temperature-moisture limits, equipment and surface tolerances are very important in this method. They have to be used carefully to prevent surface faults.

Figure 4.59. Laminated ballast and keels. (Gölpınar 2004)

The wood used in lamination method must be without natural resin and knot. Mahogany and iroko are very suitable woods for using lamination method. If wood has a natural resin, epoxy resin can not penetrate into the wood easily. If epoxy resin cannot penetrate wood, moisture penetrates in to the wood in the future.

Figure 4.60. Laminating views of hull of a Gulet. (Gölpınar 2004)

In lamination method, the wood which has 6-14% moisture ratio is cut layer by layer. Then, these layers are stricken with epoxy resins. This method is used to make keel and also to cover the board. When all parts of boat are built by this method, boat has high strength against dynamic and static loads.

If wooden board was built by lamination method, it does not occur decay. However, repairing of laminated wooden boat is easy and cheap. Repairing works are cleaning and repainting on board. So, it is enough 5 days for repairing. Because of a laminated wooden boat is lighter than conventional wooden boat, fuel and lubrication oil consumption is less. This factor occurs decreased of maintenance cost at laminated wooden boat. (Gougeon 1990, Kahraman 2000)

4.8.1.3. FRP Boat Building Method

There is a lot of method for FRP production of gulet such as conventional methods (hand lamination and spray lamination) and industrialized techniques (vacuum bag, resin transfer and SMC etc). But it is realized that while making an investment on feasibility of FRP gullets in Bodrum, the gulet manufacturers don't want to construct FRP gulet, although FRP has advantages over the other boat building materials.

FRP needs initial investment, experience and knowledge, especially for more industrialized methods. Because of this reason, the manufacturers don't want to change their construction methods. In addition to this, they think that FRP gulet will not be a attractive product for boat market because of the consumer's demands, which include aesthetic look and traditional warmness of wooden gulets.

Because of these reasons, there is not an example of FRP gulet. It can become realty if a manufacturer spend time for details of molding and make investment for equipments and information of production techniques by starting from small length of gulets.

CHAPTER 5

CONCLUSION

This study has attempted to find out the suitable material for serial production of recreational boats and to explain the manufacturing methods, which belong to this material. Tables and practical experiences knowledge, which include materials' mechanical characteristics, durability, corrosion resistance, maintenance necessity, impact resistance etc., are used for the material comparison of boats. The comparison showed that although FRP (Fiber Reinforced Plastic) has disadvantages such as high material cost, tendency to creep, less abrasion resistance according to metals, less stiffness, structural vibrations; it also has the advantages of low maintenance cost, lightweight, resistance to the marine environment, high strength, ability to mold complex shapes, easy repair, seamless construction and high heat resistance. These properties proved that its advantages greatly overshadow the disadvantages .In addition to these advantages, FRP gives the opportunity of limited production because of it's construction method which need a mold. By using the same molds, a lot of boat can be produced. Thus manufacturer gains time and the production and labor cost goes down.

GRP (Glass Reinforced Plastic) is the most common used type of FRP in boat construction industry because of its low cost. With the development of material technology, advanced FRP materials such as carbon fiber, aramid and hybrid fiber start to be used in boat construction. Although these new materials have some advantages according to GRP, because of their high price they are just used in restricted area such as race boats and special design crafts. For the future researches, researchers can investigate the usage area of these advanced composites for industrial products, a solution for the high price of the material and the usage properties for different product.

Although material and manufacture method has a big portion for being a solution for increasing market demand, the design process (where material and manufacturing methods are decided) has also another big portion on the sale of the product because of giving attractiveness to it. Even if the product has a high quality material, a product without a good design can also be unsuccessful on the market. Unlike the commercial ships, aesthetic is very important for recreational boats. It also plays an important role to sell the vessel. Therefore the design chapter, where the material choice and manufacture method is determined, is presented after introduction. In this chapter, boat design characteristics, the owner's design requirements, design process and design methods are discussed.

The exterior design, interior design, boat material and manufacture methods are parts of a whole which have to be solved with a multidisciplinary design work comprised of craftsmen, designer and engineer. The designers role is not only to draw the project with lines or working in cooperation with engineers for forming the mechanical properties, but also to deal with the boat design as a whole with material and manufacture method alternatives, to give an aesthetic look to boat, to give different interior design possibilities and to form exterior elevation alternatives which are suitable for owner's demands and needs. In Europe and USA, there are a lot of boat or yacht design schools, which play an important role on finished design's success in boat market. Because of this reason, boat/yacht design departments in universities should be activated in Turkey where the practical and theoretical knowledge comes from country's craftsmen's and engineers' past experiences and our geographical location, which already have been for the fields of manufacturing and engineering. If this knowledge and design is gathered with today's technological developments in material and production methods, our own brand can be created and by the help of this our country can get an important role in the boat market.

There are different FRP boat production methods, both conventional methods such as hand lamination and spray lamination and more industrialized methods such as SMC, vacuum bagging, and resin transfer molding. These applications all have different advantages and disadvantages when compared with each other such as time benefit, cost benefit, clean finish, and ability to mold complex shapes etc., These titles have presented as construction techniques at the former chapter of conclusion. It is found that the hand lamination and spray lamination methods (which are simple, cheap and needs less investment) are more common in use than the advanced fabricating techniques like SMC, resin transfer molding, vacuum bag (which are expensive methods needs technical knowledge but causes gain in time and labor). The proposal for an investor (while deciding the boat manufacture method) is to take care of the cost estimates for the investment, technical knowledge, and the enough space for the right equipments.

The increase of the importance of the computer usage at the stages such as design process and manufacture process for the boat market became attractive to me during the preparation of this thesis. It is mentioned that parallel to the developments at the technology; computer is very important at every stage of the design and manufacture processes such as for drawings, for evaluation of technical analysis of the boat and to form the molds at the CNC tables with computer based 3 dimensional drawings. This technology needs a fore payment but it tolerates itself by the gain at time, labor, creating complex forms. For future researchers “the computer program’s for the boat design and the computer based CNC technology’s” which affects the design and product can be a title for thesis.

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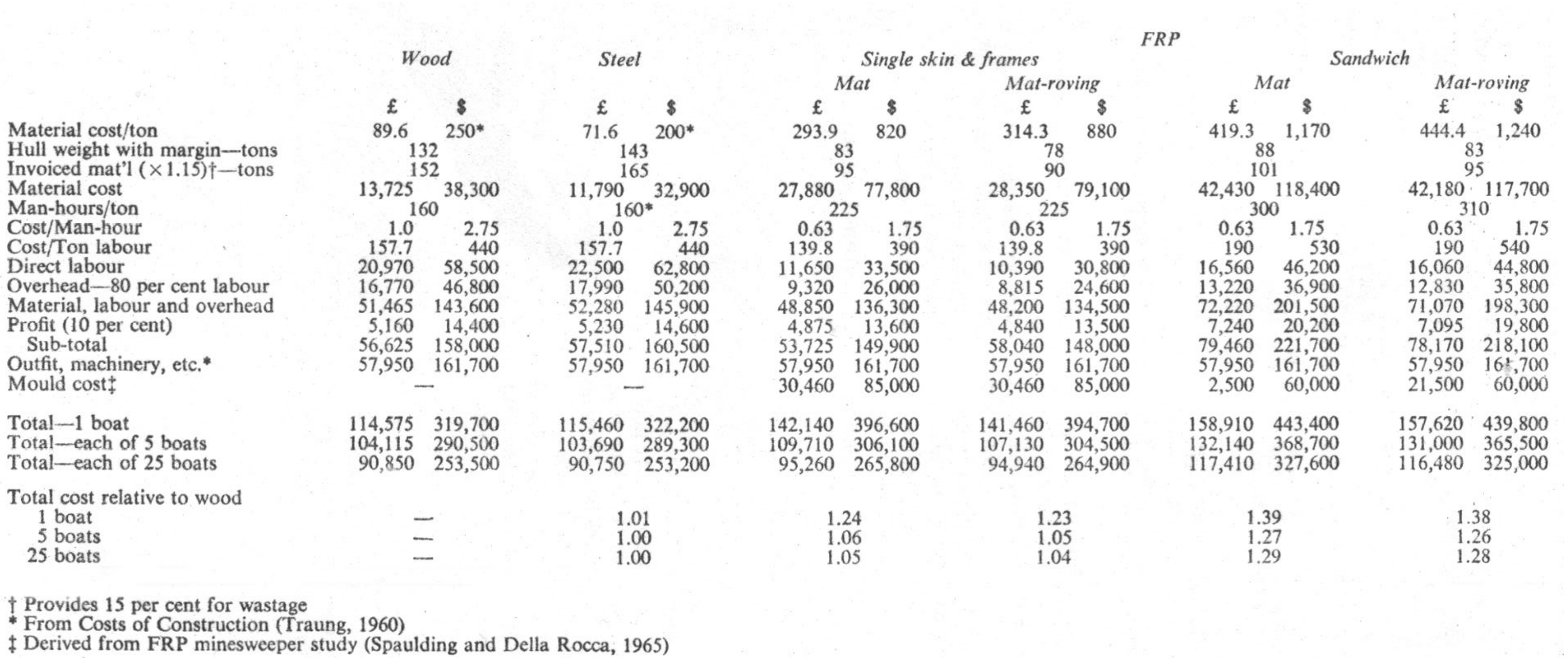

	Wood		Steel		FRP							
					Single skin & frames				*Sandwich*			
					Mat		*Mat-roving*		*Mat*		*Mat-roving*	
	£	$	£	$	£	$	£	$	£	$	£	$
Material cost/ton	89.6	250*	71.6	200*	293.9	820	314.3	880	419.3	1,170	444.4	1,240
Hull weight with margin—tons	132		143		83		78		88		83	
Invoiced mat'l (×1.15)†—tons	152		165		95		90		101		95	
Material cost	13,725	38,300	11,790	32,900	27,880	77,800	28,350	79,100	42,430	118,400	42,180	117,700
Man-hours/ton	160		160*		225		225		300		310	
Cost/Man-hour	1.0	2.75	1.0	2.75	0.63	1.75	0.63	1.75	0.63	1.75	0.63	1.75
Cost/Ton labour	157.7	440	157.7	440	139.8	390	139.8	390	190	530	190	540
Direct labour	20,970	58,500	22,500	62,800	11,650	33,500	10,390	30,800	16,560	46,200	16,060	44,800
Overhead—80 per cent labour	16,770	46,800	17,990	50,200	9,320	26,000	8,815	24,600	13,220	36,900	12,830	35,800
Material, labour and overhead	51,465	143,600	52,280	145,900	48,850	136,300	48,200	134,500	72,220	201,500	71,070	198,300
Profit (10 per cent)	5,160	14,400	5,230	14,600	4,875	13,600	4,840	13,500	7,240	20,200	7,095	19,800
Sub-total	56,625	158,000	57,510	160,500	53,725	149,900	58,040	148,000	79,460	221,700	78,170	218,100
Outfit, machinery, etc.*	57,950	161,700	57,950	161,700	57,950	161,700	57,950	161,700	57,950	161,700	57,950	161,700
Mould cost‡	—		—		30,460	85,000	30,460	85,000	2,500	60,000	21,500	60,000
Total—1 boat	114,575	319,700	115,460	322,200	142,140	396,600	141,460	394,700	158,910	443,400	157,620	439,800
Total—each of 5 boats	104,115	290,500	103,690	289,300	109,710	306,100	107,130	304,500	132,140	368,700	131,000	365,500
Total—each of 25 boats	90,850	253,500	90,750	253,200	95,260	265,800	94,940	264,900	117,410	327,600	116,480	325,000
Total cost relative to wood												
1 boat	—		1.01		1.24		1.23		1.39		1.38	
5 boats	—		1.00		1.06		1.05		1.27		1.26	
25 boats	—		1.00		1.05		1.04		1.29		1.28	

† Provides 15 per cent for wastage
* From Costs of Construction (Traung, 1960)
‡ Derived from FRP minesweeper study (Spaulding and Della Rocca, 1965)

Table a.1. Shows a cost comparison between materials used in boat construction (Traung 1978)

APPENDIX B

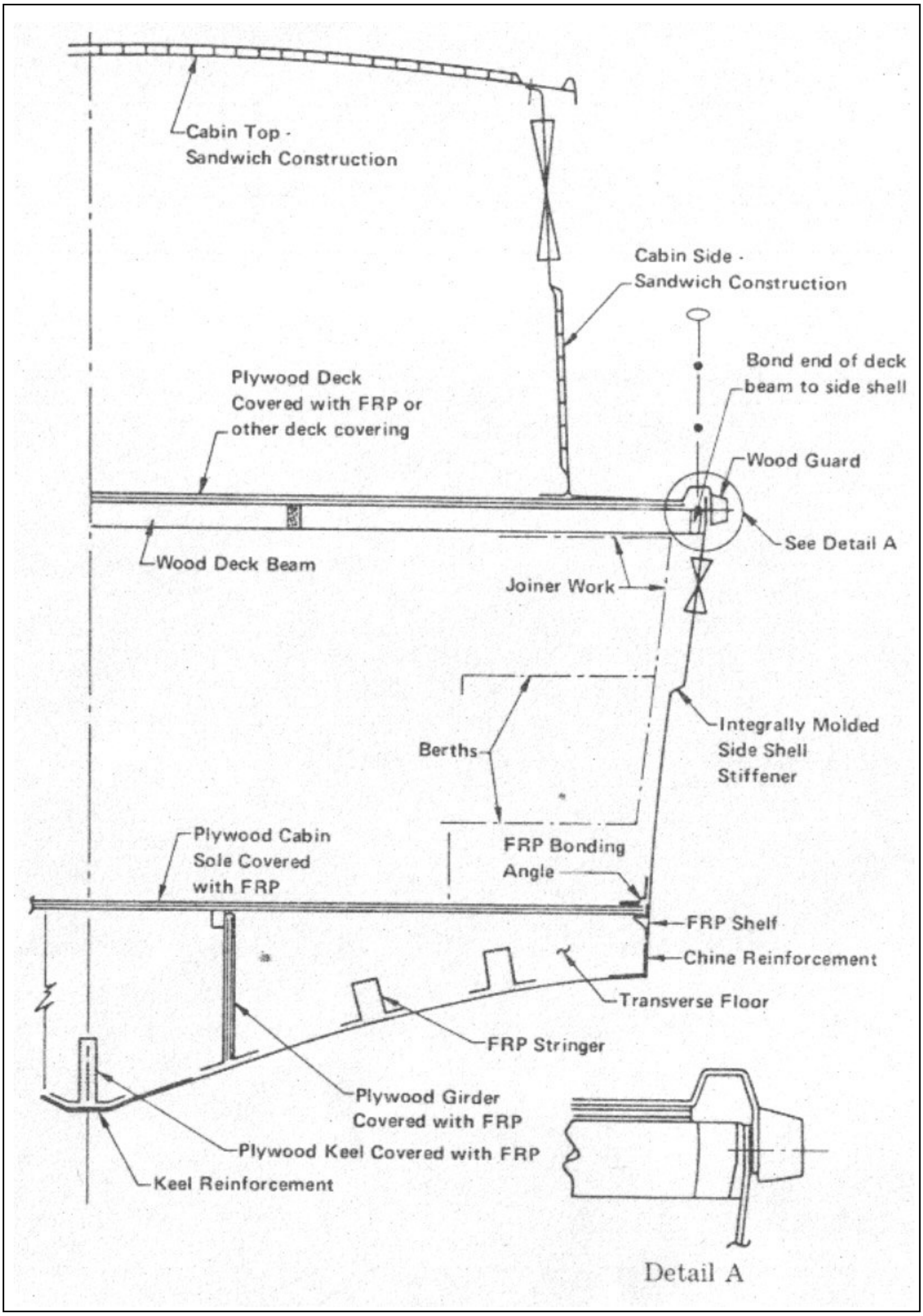

Figure b.1. Shows large power yacht midship. (Scott 1996)

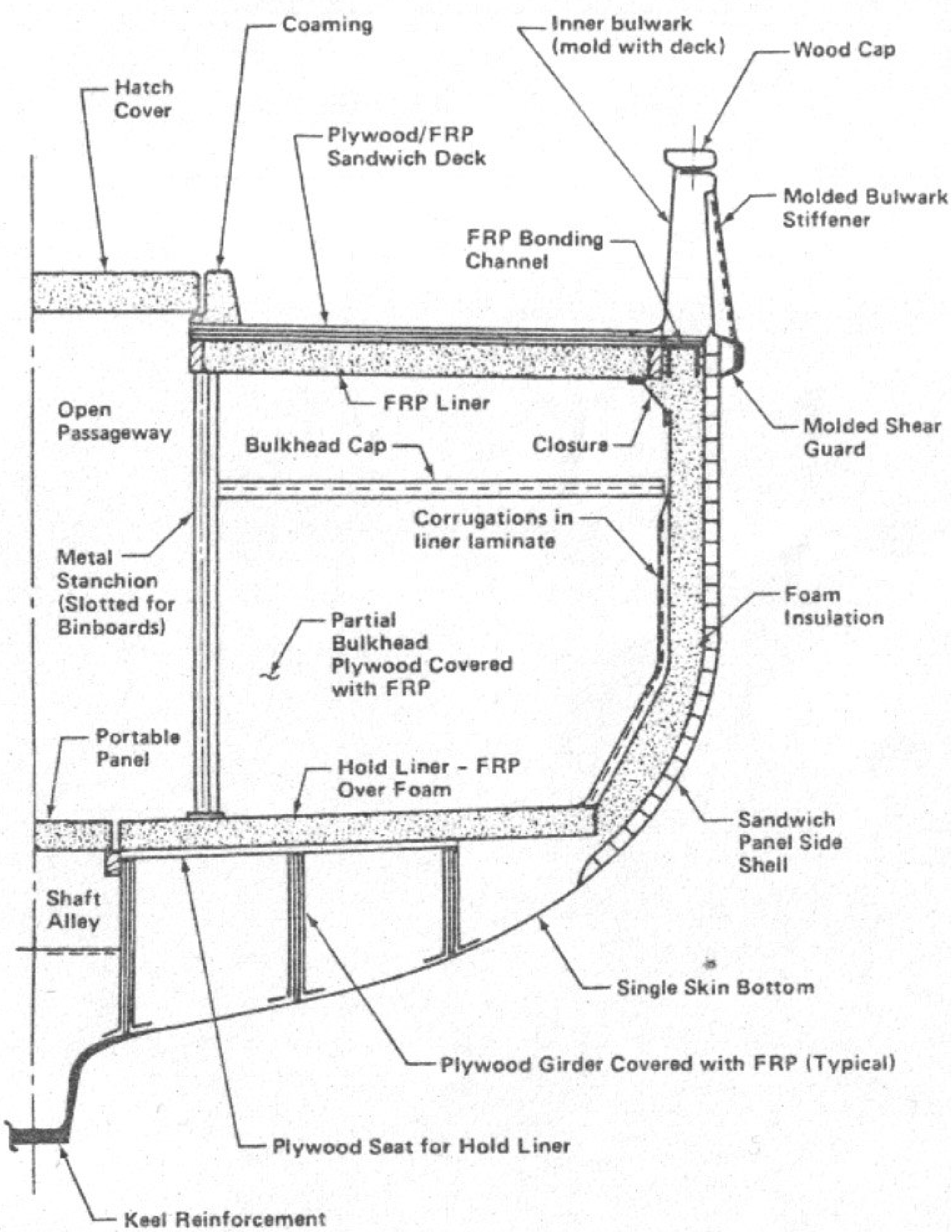

Figure b.2. Shows Shrimp trawler midship. (Scott 1996)

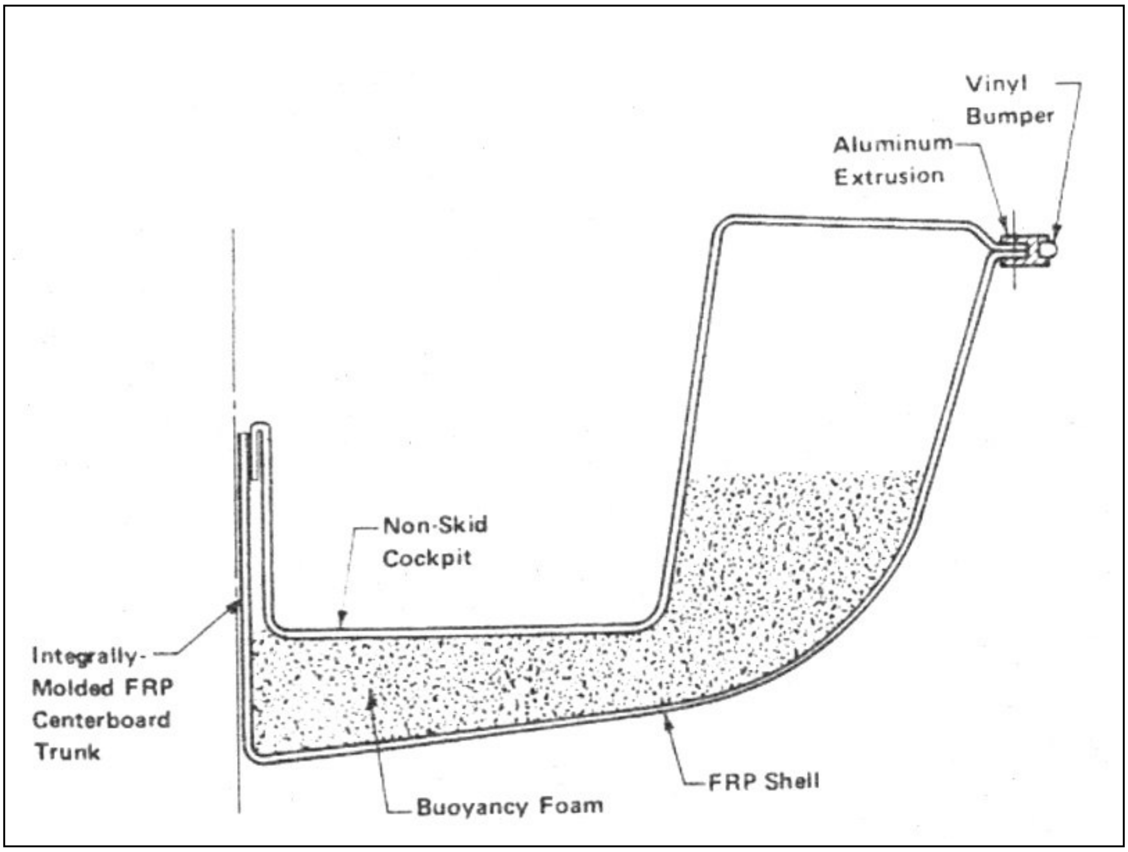

Figure b.3. Shows Small day sail boat midship. (Scott 1996)

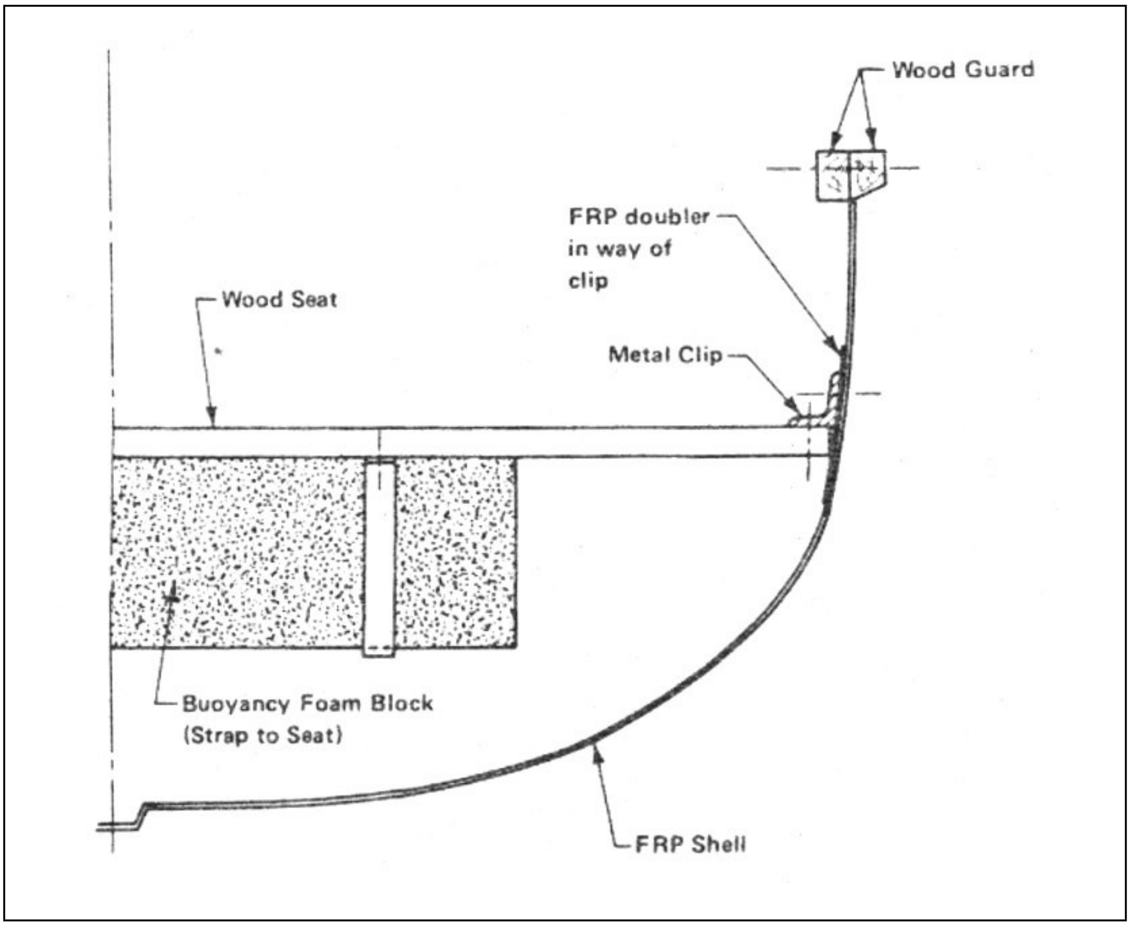

Figure b.4. Small dinghy midship. (Scott 1996)