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COMMITTEE V.8

YACHT DESIGN

COMMITTEE MANDATE

Concern for the structural design of sailing and motor yachts and similar craft. Consideration shall be given to the material selection, fabrication techniques and design procedures for yacht hull, rig and appendages. Attention should be given to structural issues associated with special fittings as large openings, inner harbours, pools etc and with security requirements. The role of standards, safety and reliability in the design and production processes should be addressed.

COMMITTEE MEMBERS

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KEYWORDS

Motor yacht, design, structures, loads, materials, outfitting

CONTENTS

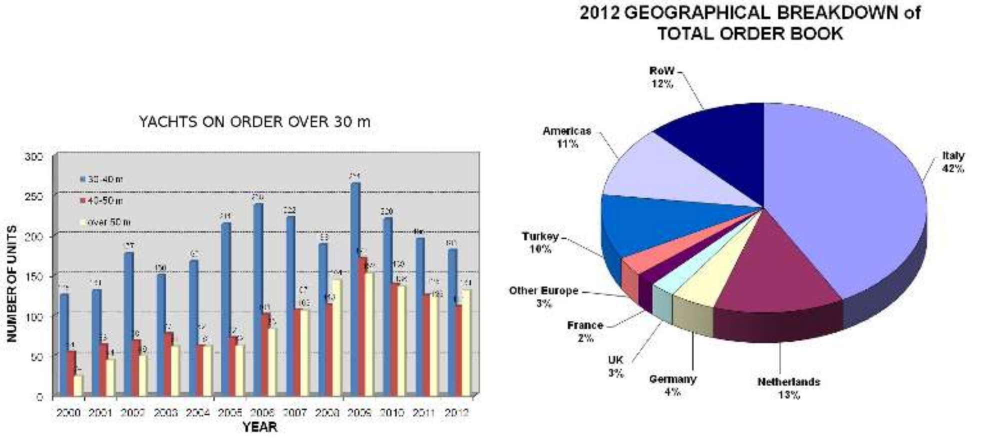
1 INTRODUCTION

Even if the term 'yacht' was coined specifically for the sailing world, this word has been associated with the concept of going to sea for pleasure purposes, and extended to include 'motor boats' as well. Nowadays, when speaking about 'yachts', one can refer both to 'sailing yachts' or 'motor yachts' and it should be specified which of the two is intended. The previous ISSC 2009 Report of V.8 Committee was specifically dedicated to sailing yachts: in this second mandate of the V.8 Committee, owing to the large size of the worldwide motor yacht market, it was decided to focus on this very important and challenging sector of the marine industry.

The term 'motor boat' generally refers to a vessel whose main propulsion is provided by a mechanic propulsion system represented, in most cases, by internal combustion engines but can include steam engines or more modern gas turbines. The first motor boats were very simple, small and wooden, and were mostly work boats. The ease of handling and the higher performance of these motor boats with respect to sailing, yachts immediately attracted the attention of the boating public and pleasure motor boats powered by combustion engines soon became very popular. The high demand for bigger, faster and more comfortable vessels made motor boats ever larger and more technologically advanced, culminating in the huge range of pleasure vessels of today, from very simple and small motor boats to highly sophisticated and extremely large motor yachts.

Nevertheless, for a long time motor yachts were designed using an 'experience-based' approach by shipyard owners and craftsmen rather than naval architects and designers, and they were considered, in a certain sense, a 'second class' category with respect to ships. Nowadays a medium size motor yacht brings with it a huge series of problems to be solved, slightly different from those associated with ships, and these vessels contain a great deal of structural and high tech equipment packed into very concentrated spaces, all aimed at raising passenger comfort and safety to a high level. Whilst, up to very recently, most designers followed tried and tested paths in order to avoid possible mistakes, at present many use advanced design techniques and 'high-tech' to make their product stand out from those of the competition. Both attitudes are motivated by the high intrinsic value of the product and a large effort is spent in research and testing.

Thanks to these recent changes, the progress in yacht design and construction has increased significantly, leading to levels of technology equivalent to or exceeding those already existing for ships. Structures in particular have been an important subject of such a development, being heavily influenced by the introduction of new construction materials (such as composites), the increase in performance and size, the need to reduce noise and vibrations, and the continuous search for new shapes and lay outs to acquire new markets. In particular, the length of the yacht represents the main discriminating factor with regard to the technical and commercial typologies of the vessels, which have given rise to the categories 'superyachts', 'mega yachts', 'giga yachts' and 'dream yachts'. However, the exact definition of these categories in terms of length are to a certain degree subjective and not clearly defined, and the only objective classification is that which divides the fleet into vessels below $24\,m$ in length ('small yachts') or over $24\,m$ ('superyachts'). The worldwide pleasure yacht fleet in 2011 consisted of approximately 23,350,000 units in total, of which 5,980 are 'superyachts'. The worldwide yearly production (2011) is approximately 550,000 small yachts units and 800 superyachts (values from The Superyacht Intelligence, 2012). The development of market



(a) (b)

Figure 1: (a) Distribution of yachts on order over 30 metres from 2000 to 2012; (b) Geographical breakdown of the total order book of yachts over 30 metres in 2012 (The Superyacht Intelligence, 2012).

share with regard to yacht length is indicated in Figure 1a, which shows the continuous growth of the demand for yachts over 30 m from 2000 to 2009 and the slight decrease started in 2010, due to the economic global crisis. The production breakdown among the various producer countries is also reported in Figure 1b, which shows the market leadership of Italy and Netherlands and the interesting growth of Turkey.

Similar to sailing yachts, the history and development of motor yacht structures can be assessed and described according to various characteristics, such as size, performance, construction materials, interior and external design. The use of wood, steel, aluminium alloys and fibre reinforced plastic for motor yacht construction are discussed with respect to the various vessel typologies, and the relevant technological aspects in the following chapters.

Other concepts which are extremely important in the world of yachting such as 'freedom', 'comfort' and 'luxury' are determinant in attracting the interest of potential owners. Even if these concepts appear to be completely separate from the practical technical aspects, as stated by Nuvolari (2011), they must be translated by designers into real features of the yacht. 'Freedom' as an example is often associated with speed, which gives to the yacht commercial impact and visibility. From the technical point of view speed involves a wide range of technical subjects, such as more powerful and lighter propulsion engines, the developments of new propeller systems and water jets, the study of new and more efficient hull shapes, but also requires the development of light and strong hull structures.

'Comfort' is mainly related to the seakeeping behaviour of the ship at sea, together with low levels of vibrations and noise on board. These two latter aspects are also closely connected to hull structures, and detailed calculations to verify the dynamic behavior of hull structures and their responses to excitations must be carried out from the first stages of structural design. As far as 'luxury' is concerned, this is an additional way to distinguish between different vessels of the same length in order to specify a higher commercial classification, and to justify any associated cost increase. Even if this aspect may sound a little ephemeral to naval architects and marine engineers, luxury is closely related to styling and fitting-out and, often, encompasses concealed technical challenges. Let’s refer, as an example, to the external finish of the yacht, i.e. the hull fairing and painting; this is a very time consuming and difficult procedure, similar to that used in the car industry, and the final result depends on the relative stiffness of both shell panels and the hull girder, as well as the paint support.

After the consideration of sailing yachts by the previous ISSC 2009 V.8 Committee, it was decided to extend to motor yachts the mandate of the same Committee for 2012. The research of this Committee has shown that little published work exists specifically concerning large motor yacht structures, and that, depending on the topology of the vessel, this subject is often assessed in a same way as for ‘ships’, or using engineering techniques and technical knowledge that is not made public for commercial reasons. Thus, as was the approach used when considering sailing yachts, much of the information obtained here has been gathered via direct contacts with shipyards and engineering technical offices.

2 MOTOR YACHT BASIC DESIGN AND TYPOLOGIES

General guidelines for motor yacht design can be found in many books and manuals such as those by Phillips-Birt (1966) and Mudie (1977). The design philosophy for motor yachts in the sixties and seventies was succinctly summarised in one sentence by Phillips-Birt: “*The variety of power yachts found in the yachting waters of the world results from mixing the four basic ingredients of design in different proportions. The ingredients are: accommodation, endurance, seaworthiness and speed. . . . The proportions of the ingredients determine the type of boat; their total amount fixes the size*”. Even if still valid for small and medium size vessels, the ‘ingredients’ for modern motor yachts now also include the present day trends of ever increasing size and opulent comfort and luxury requirements.

2.1 Motor Yacht Basic Design

There are two ways to obtain a motor yacht: to choose it from the huge number of available models on the market (and this is normally the case for small vessels) or to build a new custom (or semicustom) one according to the owner specific requirements. The attention here is focused on the latter option, as the former falls outside the scope of this report.

Despite the fact that the phases of the design for yachts are the same as those for ships and workboats, one major and very important difference exists; the aesthetics (external and interior) together with comfort and luxury requirements drive the concept, design calculation and construction of motor yachts. These qualities appear to have a major impact on the ‘dreams’ of the potential owner, and they often become his strongest motivation to buy a yacht. Nevertheless the boat must also be safe, have high levels of performance, and yet be easily managed and handled by the crew. The basic design process must consolidate these conflicting requirements via a feasibility phase (concept design) and a preliminary design, right up to the final design. A synthetic analysis of the initial design procedure of a large, high performance motor yacht is presented by Mulder (1996).

The concept design is by far the most delicate phase of the entire procedure; the client generally contacts a specialised design office or the shipyard directly, with the support of his own staff, that is composed a minimum of an architect for interior/external design, a project manager and, often, a lawyer. The initial design parameters are often very few (yacht typology, length and performance), whereas the owner and his staff are far more interested in addressing luxury items. Since the luxury items may well cause structural problems later in the design and/or construction process, the shipyard technical office must be sufficiently inventive to find solutions which make these ideas feasible. Sometimes the will to distinguish himself through his new vessel pushes the owner towards very audacious specifications which, on the one hand can give the technical team many headaches, while on the other can produce very innovative solutions. An example of fruitful synergy between a technologically advanced platform and a specific 'emotional' design framework is presented by McCartan *et al.* (2011) where the external and interior solutions are calibrated on the requirements of a specific superyacht owner.

Traditionally, the owner's desires are then transferred into paper sketches, and at this stage it is the ability of the designers to make very attractive hand drawings of external and interiors views of the yacht that are important. Even if many designers continue to prefer hand drawings, nowadays this task has been made more efficient by 3D modelling software such as *Rhinoceros*, *3DStudio*, *Think3DDesign*, *Solidthinking*, *Alias*, *Solidworks*, *Formz* etc.

If the owner decides to proceed, the preliminary design consists of initial calculations to obtain the main characteristics of the yacht, and to select the most appropriate construction materials. The subsequent process of the initial design can be started as soon as the contract has been negotiated and signed. Then the main aspects of hydrodynamics, stability and strength are assessed in more detail to be submitted to the Classification Society for approval.

During the design development great effort is spent in obtaining agreement between what the client (and stylist) wants, and what the yard can feasibly provide, but this generally results in too flexible specifications which are subject to changes through the design and building process. If the design would continue until the customer was completely satisfied, this would take far too long, and there is an economic need to mobilise the workforce in the yard before this happens. For this reason construction often starts before the design is finalised, and the risk (perhaps certainty) of the need for modifications during construction if required by the owner is accepted. This also occurs for merchant ships, but whilst in this case rework should not be necessary or at worst inexpensive, for motor yachts with luxury finishing any change implies very high cost. It is usual for disagreement on who must pay for these expensive changes to occur, and this is often only solved after recourse to a court of law.

As a matter of fact, customisation is the key point of yacht design, especially for larger vessels, and this often also reflects into structural design and construction costs. It is then necessary to have access to flexible, parametric tools for structural drawing and scantling which allow any modifications and evaluations of their consequences on the structural, outfitting and related items to be made quickly. This aspect has already been assessed in the field of cruise ships for which the solution has been found in the concurrent engineering concept (for more details see ISSC 2006, Committee Report IV.2 'Design Methods'). From this point of view designers are greatly helped by CAD software such as *Autocad*, *Microstation*, etc. and other more specialised integrated systems such as *Catia*, *SiemensNX*, *Proengineer*, etc.

An example of integrated CAD as applied to a steel superyacht is presented by Mathieu (2011); the application of modern Product Lifecycle Management (PLM) is described where all the activities and information of the early phase of the project are controlled and made available for design and engineering tasks, project management, purchasing, manufacturing preparation, and for exchanging documentation and validation with classification societies.

A new trend in yacht design is represented by the concept of Design for Disassembly (DfD) which was transferred from the automotive to the yacht industries, as maintained by Schiffer (2011). In spite of the probable, initial problems in embracing this concept as a design and production philosophy, very large advantages could arise for the yacht industry as a result.

The owners' tendency towards repeatedly requiring new and exclusive vessels, together with the continuous search by industry for new forms and layouts to develop and/or acquire new markets, often drives the design towards quite astonishing radical and innovative solutions and new vessel typologies. For example, the transition from traditional stern shapes to the new 'swim platform' shape, the present vogue of reverse bows, or the *Wally Power* motor yacht, whose minimal lines and huge power made it a reference point for this new style.

2.2 Motor Yacht Typologies

The first known motor vessel was *Pyroscaphe*, a 148' wooden side-wheeler boat powered by a double-action steam machine. Built by Marquis de Jouffroy d'Abbans, this vessel made its first demonstration run on 15 July 1783 on the river Saone in France. The origins of motor yachting date back to 1830, when a rich Englishman commissioned the first known private motor yacht, the 130' steam-powered *Menai* designed by Robert Napier and built on the Clyde, Scotland. In 1857, on Como Lake in Italy, Barsanti and Matteucci experimented with a boat powered by an internal combustion engine. In 1883, the first horizontal internal combustion engine was created in Germany by Gottlieb Daimler. In 1886 a launch, called *Neckar*, with a twin cylinder combustion engine was tested on the Waldsee in Cannstatt in Germany.

The majority of present day motor yacht forms arose from the review and development of very old typologies. As an example, 'lobster boats', which were born at the very end of the 1800's in the U.S.A., originated from work boats and later became sophisticated pleasure yachts, only keeping the lines and lay out of the original vessels. Also, in the early 1900's a particular motor boat was designed to meet the requirements of business men living in Long Island who had to reach the New York Centre quickly: named the 'Fast Commuter' it can be considered the direct progenitor of present cruiser yachts.

At present the world-wide motor yacht fleet is composed of a huge quantity of vessels of many different typologies: in order to give a manageable overview of these typologies, the most important yacht categories are briefly outlined below as a function of relevant commercial and technical characteristics. From the commercial point of view the main subdivision is between sailing and motor yachts; this principle has been assumed by the V.8 Committee itself which assessed first sailing yachts in the 2009 Report and then motor yachts in the present 2012 Report.

Within motor yachts the most common subdivision is relative to the yacht overall length L_{oa}, since this parameter is a reference figure for technical, bureaucratic and commercial operations. At present, the worldwide accepted criterion is that of separating yachts with an overall length below or above $24\,m$, the latter vessels considered by classification societies (CS) as 'pleasure ships'. At lengths greater than this yachts are further subdivided into more subjective categories such as 'mega yachts', 'giga yachts', 'dream yachts' but without any clear objective correspondence to a length range. Below $24\,m$ in length the subdivision often depends on the local classification societies and/or flag rules.

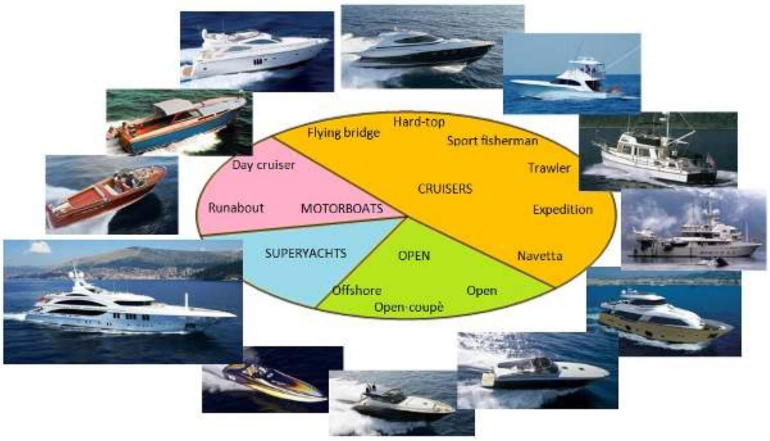


Figure 2: Motor yacht main typologies

A third subdivision refers to the hull typology: monohull or multihull. While catamaran and trimaran configurations are widely diffused in the sailing world, very few examples of multihulls exist as motor yachts, the great majority being represented by monohulls. Also related to the hull shape, motor yachts can be divided into displacement vessels, with a traditional round hull, and planing vessels with a hard chine hull and a flat bottom.

The last subdivision, probably the most important from the structural point of view, is relative to the construction material which heavily influences the design procedure and production technologies. In the following a brief description of the most important yacht typologies is presented, as summarised in Figure 2.

2.2.1 Motor Boats

In the 1930's, with the improvement of internal combustion engines with regards to power, weight and cost, the boat industry identified an attractive new business sector in the diffusion of boating at a popular level. Intensive production of small and fast motor boats took place and in few years many new shipyards were born on the American and European coasts. A typical product of this trend was the 'runabout'; with lengths below 8 or $9\,m$, planing hulls and equipped with petrol engines derived from the car industry they can reach speeds over $30\,knots$. Completely built in wood (cedar or mahogany planking over oak frames), glued and riveted by copper bolts, they had no deck, with all crew spaces completely open to the elements, or at most covered by a small tent or removable hardtop. They had the same layout of a car with seats, benches, sun beds and driving position with complex dashboards. Very famous names for this typology are Chris Craft, Gar Wood and Hacker of the USA and Riva of Italy.

With the introduction of fibre reinforced plastic (FRP) in the sixties the advantages of series production pushed this category towards great commercial success which still continues today. Even if still inspired by the original typology, commercial competitiveness made runabouts more luxurious, complex and high performance. With a small increase in length (up to $12\,m$) runabout became 'day cruisers' with a closed accommodation space below the foredeck fitted with a double bed, kitchen area and toilet to allow for short day cruises or coastal passages.

2.2.2 Cruisers

Cruisers are medium to large size boats with a continuous deck and large covered areas below or upon that deck which allow for full living quarters. The exterior aspect is characterized by the presence of an extended length superstructure along a significant portion of the boat. The most valuable spaces are those on the main deck, owner and guest night cabins (with bathrooms), normally lying below the main deck. The external space is fitted with a cockpit astern, for outdoor living, and a sunbathing area towards the bow.

Superstructures can be extended across the whole width of the boat, with a solution called 'wide body superstructure' which allows for larger spaces inside, or they leave space for a gangway of about 0.8 to $1\,m$ along each side to allow easy access from stern to bow (walk around superstructure). On larger yachts a mixed solution is often assumed with a walk around solution astern and a wide body at the bow to maximise the internal spaces as far as possible. If the deck above the superstructure is accessible, it can be fitted with seats, sofas and a second set of driving controls. In this case the yacht is said to have a flying-bridge configuration; this is the most common and appreciated configuration and often gives the name to this category. If the roof of the superstructure is not accessible and it functions as a simple shelter of the internal spaces, the boat is said to have a hard top configuration. Depending on the yacht performance, hulls can be either displacement, semi-planing or planing and are mostly equipped with two engines either with an in-line or V configuration.

A large number of different versions with particular characteristics fall within the cruiser category, which form separate subcategories such as 'sport fisherman' and 'trawlers', which are derived from the evolution of sports fishing boats developed in the United States in the early twentieth century. 'Expedition' (or adventure) yachts have been recently introduced into the market and aimed at owners interested in visiting extreme sea areas characterised, mainly, by the presence of very cold water and floating ice. The first expedition yachts derived from the refitting of old tugs or supply vessels with luxury interiors. Now they are usually new builds from specific new designs (Bray, 2008), and both the demand for and the dimensions of these vessels are increasing every year. 'Navetta' is an Italian term (in English: 'small ship') coined to indicate a motor yacht specifically designed to give excellent levels of onboard comfort during navigation, without demanding excessively high speeds. The relatively short length (not more than $30\,m$), the necessity to provide large interior spaces and consequently voluminous superstructures, gives such vessels squat lines, making them in some aspects similar to a short ship.

2.2.3 Open

The term *open* indicates a relatively large motor yacht without superstructures and with a wide open area astern protected only by a simple wind screen. This arrangement gives the vessel very 'narrow' and sporty lines combined with spacious and comfortable interiors and very high performances thanks to planing hulls and powerful engines. Open yachts have a single deck extending approximately along the fore half of the boat length and a large cockpit astern, protected by a windshield that extends to the sides to form a kind of bulwark protection. The space below deck is devoted to accommodation and living areas with one or more cabins, depending on the size of the yacht.

Some slightly different versions of the same typology are available; 'Offshore' yachts are a sport version with smaller dimensions but with speeds similar to those of offshore racing powerboats. Living spaces on board are limited and the layout is very basic to underline the sporty character of these vessels and to minimize the weight. Engines may best be described as exuberant and, together with the fuel, occupy a good portion of the available interior volume. *Open Coupè* is a modern compromise between an open and a hard top yacht: it has a lay out similar to that of a hard top yacht, but has a sliding roof which allows the transformation of the protected space under the superstructure into an open area.

2.2.4 Superyachts

Superyachts represent the development of cruisers in terms of increasing length, resulting from the requirements of very exigent owners looking for an absolutely exclusive and unrepeatable product. This was once attainable only by royal families and very important industrial or business men. Even if actually closer to ships than to yachts, some excellent historical examples should be mentioned as the first 'mega yacht': the *Savoia Royal Ship*, 133 m, built in 1883 in Castellamare di Stabia (Italy), the German imperial yacht *Hoenzollern II*, 120 m, built in 1893 in Stettin and the *Victoria and Albert III* Royal Yacht, 116 m long, built in 1901 by Pembroke Doc shipyards in Scotland. In the USA Herreshoff shipyards built more than 200 motor boats between 1878 and 1945, the most famous of which are the steam commuter 81 *ft Mirage* (1910) built for C. Vanderbilt, and the 114 *ft Navette* (1917) built for Jack Morgan. In Europe, the Ailsa Shipyard in Scotland built the first steel superyacht *Triton* in 1902. At 55.4 m long, this vessel operated in the British Royal Navy as a Royal Patrol Yacht during World War II.

The size of superyachts changed over the years (Figure 3), with a continuous enlargement until the Second World War, peaking with the construction of *Savarona*, a 136 m yacht built by Blohm & Voss in 1936 and destined to be the biggest yacht afloat for nearly 50 years. After the end of World War II there was a sensible reduction in average yacht dimensions, with the only exception being the 125 m Royal Yacht *Britannia*, launched in 1953 by John Brown's Shipyard in Clydebank. Only in the eighties the size of the largest yachts start to increase once more; in 1980 Benetti Shipyards launched *Nabila*, 86 m in length and, few years later, in 1984 the 144 m yacht *Abdul Aziz* built by Helsingor Vaerft in Denmark, became the largest yacht in the world.

Nowadays a huge number of superyachts and a relatively high number of vessels of over 50 m are built every year and the demand for these vessels and for ever increasing dimensions and opulence seems not to slow down, although the current global economic

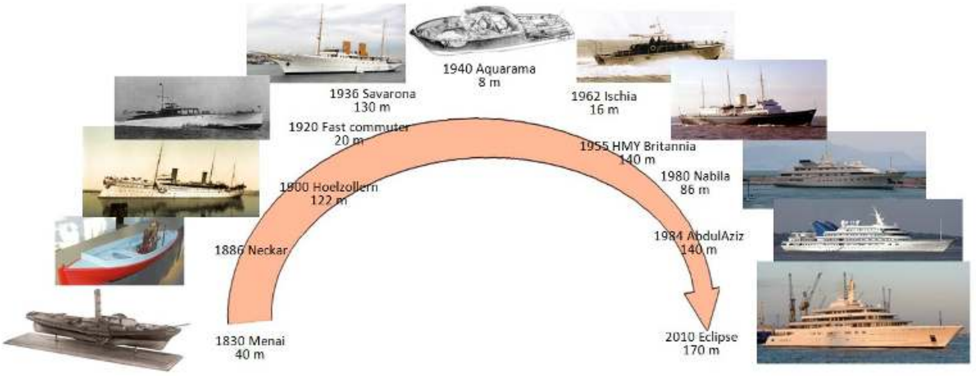


Figure 3: Development of yacht dimensions from the beginning till present days.

climate has cooled this previously rampant industry in recent years. An emblematic characteristic of superyachts is the large number of decks, giving the superstructures an imposing appearance, and very large internal spaces. The length of a superyacht is the defining characteristic, so the vessel's typology can be any of those previously described; hence, there are very large flying bridge, open and expedition yachts. At present the largest yacht in the world is M/Y *Eclipse*, at 164 m in length, delivered in 2010 by Lürssen Shipyards in Germany, and there are over 25 yachts of L_{OA} greater than 100 m.

3 RULES AND REGULATIONS

There is a wide variety of national and international rules and regulations for which motor yachts must adhere. In addition to the rules from CS, the International Maritime Organisation (IMO), National Regulations, and Port State Regulations, large motor yachts must meet the following International Conventions:

- Safety of Life at Sea (SOLAS);
- International Load Line Convention (ILLC);
- MARPOL, devoted to the control of the marine pollution;
- International Regulations for Preventing Collisions at Sea (COLREG), which provides requirements for steering and sailing, navigation lights and sound signals;
- Standards of Training, Certification and Watchkeeping (STCW).

The rule's applicability depends on yacht characteristics such as dimensions (represented mainly by load line length and gross tonnage), the type of service and the number of passengers. Yachts are subdivided into two main categories: superyachts with a freeboard length over 24 m and yachts below 24 m. While superyachts are subject to international rules, yachts below 24 m are considered differently by the various flag administrations. The reference length itself is not defined everywhere in the same way. For example in the European community, all the pleasure yachts built and commercialised in the EU with a hull length, L_H, between 2.5 and 24 m should be 'CE Marked' and comply with ISO Standard Rules. A further category of yachts below 12 m is also defined for which less stringent rules apply.

The type of service is important and can be designed and managed for a private use or a commercial use:

- private yachts are designed and managed for the personal use of the owner and should not be engaged in any kind of trade;
- commercial yachts are designed and managed in order to allow charter activity (trade). However, at times they might also be registered and managed as private yachts.

Private yachts are required to comply with MARPOL Rules, the International Tonnage Convention and COLREG. Private yachts need not to comply with the requirements of ILLC and SOLAS.

Large commercial yachts are equivalent to ships and must comply with International Conventions. Because the International Conventions have been written and issued mainly for cargo and passenger ships, in 1997 the UK Maritime and Coastguard Agency (MCA) developed the 'Code of Practice for the Safety of Large Commercial Sailing and Motor Vessels', known as the MCA Large Yacht Code (LY1), which adapted the International Conventions for yachts, allowing them to maintain their particular identity. In 2004 it was updated to Large Yacht Code 2 (LY2). Even

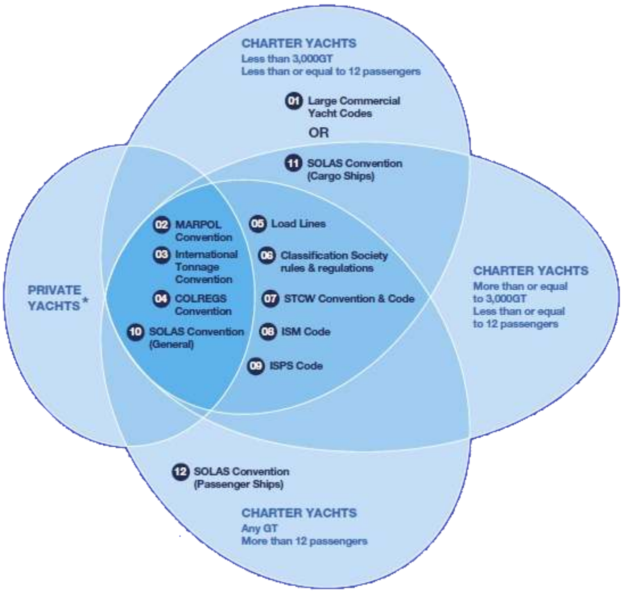


Figure 4: Schematic representation of rule requirements for private and commercial yachts (Manta Maritime, 2008).

though the LY2 is a statutory regulation for only the UK and Red Ensign flag charter yachts, LY2 has been the most frequently used Code by the industry all over the world. Fairbrother (2006) presents the main aspects of this code and highlights the most important topics. The MCA-LY2 (as LY1) recognizes American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV), Germanischer Lloyd (GL), Lloyd's Register (LR) and Registro Italiano Navale (RINA) as the CS that have rules prescribing the required standards for construction and strength of large motor yachts. In addition, CS are authorised to carry out plan approval, surveys and issue certificates of compliance with certain parts of the MCA Large Commercial Yacht Code on behalf of the MCA, the CISR (Cayman Islands Shipping Registry), and other Red Ensign Administrations.

The Regulation environment is efficiently presented in Figure 4 (Manta Maritime, 2008) as a function of private and commercial use. Commercial yachts can be further subdivided into three main categories depending on the gross tonnage and the passenger number:

1. Commercial yachts with a freeboard length over $24\,m$, equal to or below $500\,GT$ and carrying a maximum of 12 passengers should comply with MCA-LY2 or equivalent. The limit of $500\,GT$ corresponds to a length of approximately $45\,m$ for a normal motor yacht with standard superstructures and up to $55\,m$ for a large sailing yacht (with small superstructures). Specific less stringent rules are considered by LY2 for 'Short Range Yachts' with less than $300\,GT$ and a navigation limit of 60 nautical miles. Classification with one of the major CS is mandatory. Commercial yachts with a freeboard length below $24\,m$ should comply with different codes, i.e. MCA MGN 280 the 'Code for Small Vessels in Commercial Use for Sport or Pleasure' (1997); classification is not compulsory.
2. Commercial yachts as above, but with a gross tonnage up to $3000\,GT$ and with less than or equal to 12 passengers should comply with the MCA-LY2 as well;

in this case LY2 contains more stringent requirements about safety and arrangements in general because, from the SOLAS point of view, differences between these yachts and merchant ships are reduced. The limit of $3000\,GT$ corresponds to an overall length of about $90\,m$. For this category of yachts classification is mandatory.

3. Commercial yachts above $3000\,GT$ or carrying more than 12 passengers and up to 36 passengers should comply with the MCA 'Passenger Yacht Code' (2010). It applies to yachts with a maximum number of persons equal to 99, crew components included. Above this limit commercial yachts should fully comply with SOLAS Rules, without the Large Yacht Code 'smoothing interpretation'. Classification is necessary.

Further comments on the role of CS for charter yachts are contained in Cooper *et al.* (2009) and in Strachan and Lagoumidou (2009). The structural design and scantlings of any kind of yacht are regulated by CS' rules; as a matter of fact, very limited structural aspects are contained in MCA-LY2. Of the 30 sections in MCA-LY2 only one (Section 4) is relative to structures. It initially states that the purpose of this section is *to ensure that all vessels are constructed to a consistent standard in respect of strength and watertight integrity.* Concerning structural strength, LY2 reports that *all vessels must be classed.* It follows a brief discussion about watertight bulkheads and sailing yacht rigging. The remainder of MCA-LY2 contains mainly rules concerning watertight integrity, machinery, electrical installations, steering gear, bilge pumping, stability, freeboard, life saving appliances, fire safety, navigation equipments, anchoring and other issues related to protection and safety.

In the following, synopses of structural issues contained in the rules and regulations of the most important CS are presented. Details of the design loads used by the major CS are presented in Chapter 4 of this report.

The International Standards Organisation in 2005 completed the standard number 12215 'Small Craft - Hull Construction and Scantlings', mandatory for all commercial motor and sailing boats with an hull length between 2.5 and $24\,m$ in the European Union. Although ISO Standards were built on the ABS 'Guide for Building and Classing of Pleasure Motor Yachts', there are a number of differences between ISO 12215 and the ABS Rules. ISO 12215 is, to some extent, a design standard more than a set of rules. Curry (2005) presents a comprehensive assessment of ISO 12215 in which all main parts are discussed, verified and compared with the principal CS' rules.

ISO 12215 is divided into 8 Parts. The first three parts are devoted to materials and they provide minimum required mechanical properties for composite single skin laminates, sandwich cores (foam and balsa), steel, aluminium and wood. Part 4 deals with workshop and manufacturing. Part 5 (2004) involves design pressure, design stresses, and scantling determination. Part 6 (2005) presents structural arrangements and details. Part 7 (at present under development) is dedicated to the scantling determination of multihulls and Part 8 is dedicated to rudder design. The sections of specific interest for structure design are ISO 12215-5 'Small Crafts, Hull construction and Scantlings' Parts 5 and 6.

In ISO standards 12215-5 (2004) motor yachts are divided into four design categories depending on the service range, wave heights and wind speed. As the standard doesn't take into account hull girder strength, the scantlings are assumed to be governed by local loads defined as sea pressures. Equations for shell thickness and reinforcement modulus are provided for both motor and sailing craft. Shell thickness calculations depend on the construction material considered by ISO 12215 (wood, steel, aluminium, FRP single skin and sandwich). The section modulus is calculated with a unique procedure independent of the material. In all cases, equations that contain the design pressure and the material design stress σ_d, are provided by the Standards. Simplified scantling methods are provided as well in appendages for boats with hull lengths less than $12\,m$ and sailing boats less than $9\,m$, design categories C and D (limited navigation) respectively. Other appendages conclude this part with very detailed specifications for material characteristics.

ISO 12215-6 (2005) deals with general structural arrangements, transverse and longitudinal structures, and structural details. Particular attention is devoted to deck and shell openings, FRP local reinforcements, hull-deck joints, steel and wood details and, finally, to rudder and keel structural arrangements and connections. A number of appendages concern glued and riveted joints with calculation procedures and application examples.

American Bureau of Shipping in 2000 published the ’Guide for Building and Classing of Motor Pleasure Yachts’, which is applicable to *motor pleasure craft* $24\,m$ *(*$79\,ft$*) or greater in overall length up to* $61\,m$ *(*$200\,ft$*) in length, that are not required to be assigned a load line.* The rules are composed of 24 sections, 10 of which, from Section 3 to Section 12, are concerned with structural scantlings. Section 3 contains general definitions, such as effective width of plating and bracket standard proportions. In Section 4, mechanical properties of materials are defined in detail; steel, aluminium alloys, FRP and wood are all considered. In Sections 6 and 7, structural arrangements, details and fastenings are presented for all the materials considered by the rules. As for design loads, considered in Section 8, hull scantlings are considered separately for high speed craft and displacement craft. Section 9 deals with high speed craft, defined as craft having a maximum speed in knots not less than $2.36L^{0.5}$ where L is the scantling length in metres. Minimum thicknesses for plating and minimum section modulus for internals are defined for steel, aluminium, FRP and wood. Formulas for minimum thickness of shells and minimum section modulus of reinforcements are provided as a function of design pressure, material design stress, stiffener span and spacing. The same formulation is assumed in Section 10 for hull scantlings of displacement craft. The special structure of stem and stern frames, keels, shaft and rudders are considered as well by the ABS Rules in Sections 12 and 13.

Bureau Veritas ‘Rules for the Classification and Certification of Yachts’ (2012) applies to ships intended for pleasure or commercial cruising and with a length not exceeding $100\,m$. A lower limit on length is not mentioned, but it is stated that European flagged craft less than $24\,m$ must meet the EC directive. BV Rules are applicable to sailing and motor vessels of monohull and catamaran type, built in steel, aluminium, wood and composite materials. Rules are organized in three parts: Part A is related to Classification and Surveys, Part B to Hull and Stability, and Part C deals with Machinery, Electricity, Automation and Fire Protection.

Structure scantlings are considered in Part B, from Chapter 4 to Chapter 8. Scantling requirements are influenced by the navigation notation (‘n’ coefficient). Design loads are provided in terms of overall global loads and local loads, both static and dynamic, in Chapters 4 to 7.

Plating and stiffener scantlings are assessed in Chapter 6 for steel and aluminium and in Chapter 7 for composite and plywood vessels. Minimum thicknesses for plating are defined as a function of geometric characteristics of the panel (aspect ratio and smaller side), design pressure and material admissible stress. In the case of stiffeners, scantlings are sized with regards to a minimum section modulus and a minimum shear area given by formulas containing design pressure, material admissible stress, span and spacing of the stiffeners. For both plating and stiffeners, a procedure for a buckling check is presented. The BV rules also provide general considerations for structural layout and construction details of bottom, side, deck and superstructures areas.

Det Norske Veritas Regulations for motor yachts are included in the 'High Speed, Light Craft and Naval Surface Craft' Rules (2011) which consist of 8 Parts; Parts 0 and 1 contain general regulations, Part 2 metallic materials, welding and composites, Part 3 structure and equipment requirements, Part 4 machinery and systems/equipment and operation, Part 5 special service and type, Part 6 special equipments and systems, Part 7 HSLC in operation.

Yachts are then considered as a 'type' among other special service vessels and the rules apply to yachts over $24\,m$ in length, *not intended for operation on a commercial basis, i.e. that the operation of the craft is being financed by others than those on board.* The following classes are defined:

- ✠ 1 A1 LC Yacht: when the displacement fully loaded is not more than $(0{,}20 \cdot L \cdot B)^{1{,}5}$. Vessels with a larger displacement can be assigned the notation based on special considerations;
- ✠ 1 A1 HSLC Yacht: when the displacement fully loaded is not more than $(0{,}16 \cdot L \cdot B)^{1{,}5}$ and its maximum speed exceeds $3L^{0{,}5}$.

No mention is made of length, except for the note that recreational boats less than $24\,m$ may have to comply with the European Union Directive for CE marking. There are also no specific stipulations concerning loadings in this part, and in this respect yachts are considered with other craft in Part 3, Chapter 1.

Structural scantlings are dealt with mainly in Parts 2 and 3 which are dedicated to the hull structural design of steel and aluminium yachts; the general outlines for each chapter are very similar. Design loads, in Chapter 1 of Part 3, are subdivided into local and global loads. After a detailed description of bottom, side, deck, bulkhead and superstructure layouts, common design rules for most important details are presented. Material and welding characteristics, provided in the following sections, should be integrated according to Part 2 specifically dedicated to materials. Hull structure scantlings starts with the verification of a minimum hull section modulus. Plating minimum thicknesses are given by simple formulas containing, as usual, design pressures and stiffener spacing. Reinforcement scantlings are considered by DNV separately for secondary stiffeners and primary web frames and girders. In both cases the minimum section modulus should be calculated by formulas as a function of span, spacing, design pressure and allowable material stress. The rules also give a procedure for buckling control of plating, stiffeners, stiffened panels and girders.

Chapter 4 deals with composite hull structures; requirements about material manufacturing procedures and main characteristics are presented. This part should be integrated by other requirements contained in Chapter 4 of Part 2. The scantlings of FRP single skin construction is based on a minimum glass weight per square metre given by a table as a function of structural member and hull position. As the minimum content of fibres by volume is fixed by DNV at 25 %, the corresponding thickness comes accordingly as a function of the utilised glass fabrics. A specific section is dedicated to sandwich panels. FRP reinforcement scantlings are based on a direct approach starting from the definition of a maximum bending moment (calculated as a function of span, spacing and design pressure) and a subsequent verification of the cross section modulus as a function of the design stress of the material.

Germanischer Lloyd classifies motor and sailing yachts in Part 3 of their rules for 'Special Craft'. Chapter 2 (2003) applies to motor and sailing yachts with a scantling length greater than $24\,m$ for private, recreational use. Chapter 3 (2003) is related to motor and sailing yachts with a length between 6 and $24\,m$ for private use. GL specifies that Rules for Special Craft were developed considering that yachts, with respect to merchant ships, are usually subjected to:

- less severe operating conditions than for ships in regular trade;
- limited yearly sea hours in relation to harbour hours;
- special care by the owner and usually good maintenance.

Two categories of yachts are considered: yachts with scantling lengths between 24 and $48\,m$ and yachts over $48\,m$. In the first part of Chapter 2 the first category is assessed. Normal and high strength steel, aluminium and wood are covered by this section. For FRP and core materials reference should be made to a specific part of the GL Rules II – Materials and Welding, Part 2 – Non-metallic Materials, Chapter 1 – Fibre Reinforced Plastics and Adhesive Joints.

In Section 2.C a list of general criteria are provided in detail regarding, as an example, curved panel and girder correction factors, reinforcement span definition, effective width of plating, buckling evaluation criteria and others. Section 2.D is devoted to steel and aluminium structures. Design loads are defined as a function of a vessel's speed. Minimum plating thickness of hull, decks, superstructures, bulkheads and tanks is calculated by a unique formula containing design pressure, permissible stress of the material, dimension parameters and a correction factor for curved panels; an additional corrosion allowance is considered as well. In the same way the minimum section modulus of stiffening members is provided by a unique formula for stiffeners, frames, floors, beams and girders. The formula contains the usual parameters such as span, spacing, design pressure and material permissible stress. Pillar scantling and buckling verification is considered separately in a specific section.

Composite material hulls are considered in Section 2.E. For composite hull design loads, the same criteria as steel vessels are assumed. Plating and stiffener scantlings follow a different approach being based on classic beam/plate and laminate theory. Wooden yachts are briefly discussed in Section 2.F; the structural scantlings should comply with GL 'Rules for Classification and Construction of Wooden Seagoing Ships'.

Section 2.G deals with motor and sailing yachts with lengths exceeding $48\,m$ and with steel and aluminium structures. Again, for high speed vessels reference should be made to GL HSC code (Part 3 - Special Craft, Chapter 1 - High Speed Craft, 2012). In the case of moderate speeds, scantlings should comply with the GL Rules Part 1 – Seagoing Ships, Chapter 1 – Hull Structure (2012).

As already pointed out, GL Rules have a specific section (GL, Special Craft – Yachts and Boats up to 24 m) for pleasure craft with length between 6 and $24\,m$. Also commercial vessels can be considered by these rules with certain add-on-factors taken into account. The chapter contains its own general rules and definitions mainly addressed to FRP construction and a detailed description of the material mechanical properties by means of empirical formulas and tables based on the laminate glass content by weight. The scantlings of plating are given in terms of glass weight (in g/m^2) of shells (keel, bottom and side) by formulas as a function of stiffener spacing, design pressure and speed correction factors. Minimum section moduli are provided for transverse and longitudinal reinforcements by formulas containing reinforcement span, spacing, design pressures and speed correction factors.

Lloyd's Register of Shipping Rules for motor yachts are contained in the 'Rules and Regulations for the Classification of Special Service Craft' (2011). According to LR definition *a yacht is a recreational craft used for sport or pleasure and may be propelled mechanically, by sail or by a combination of both.* The rules are applicable to high speed craft, light displacement craft, multi-hull craft (both motor or sailing) constructed from steel, aluminium alloy, composite materials with an overall length between 24 and 150 m. The rules are composed of 17 Parts and the hull scantlings are assessed in Parts from 3 to 8. Part 3 introduces structural definitions and nomenclature, building tolerances and limits for geometrical defects due to welding for steel and aluminium. Some basic principles about structural continuity, fore and aft arrangements, bulkhead distribution and structure, and properties of beam sections are covered as well. At the end a comprehensive assessment of rudders, shaft brackets and other outfit components are presented. Part 4 reports additional information for yachts regarding water-sport platforms and shell openings, deck safety equipment, portlights and windows, protection of openings, corrosion protection, intact and damaged stability together with some special rules for sailing yachts.

Part 5 opens the structural scantling section with the definition of design load criteria. Parts 6, 7 and 8 contain scantling procedures for steel, aluminium and FRP vessel respectively. Parts 6 and 7 have the same lay out; in particular minimum plating thickness and stiffener modulus are governed by same equations as a function of design pressure, minimum yield strength of the material and usual geometrical parameters (stiffener spacing and span, panel aspect ratio etc.). In both parts, a table with minimum thickness requirements for different hull locations and vessel typologies is provided as a function of the material coefficient and of the yacht length. FRP is discussed in Part 8 because different approaches are necessary due to the very different nature of the material. The section provides mechanical properties of laminates as a function of glass content and reinforcement type (mat, woven roving, cross lied and unidirectional) together with nominal thickness of a single ply. The minimum plate thickness is defined by formulas as a function of service factor depending on service type notation, while the minimum thickness of laminate for both stiffener and laminated components are based on an assumed fibre content $f_c = 0.5$. The final chapters of all three Parts 6, 7 and 8 are dedicated to hull girder strength for mono and multi-hull and failure mode control. This last section provides criteria to evaluate deflection, stresses, buckling and vibrations.

Registro Italiano Navale Rules for yachts are published in two versions: 'Rules for the Classifications of Pleasure Yachts' (2011), which applies to yachts *engaged in private use of a length of* 16 m *and over* and 'Rules for the Classification of Yachts Designed for Commercial Use' (2011a) addressed to commercial vessels with length of 24 m and over. The two versions have an identical formulation, divided into five parts: Part A 'Classification and Surveys', Part B 'Hull and Stability', Part C 'Machinery, Electrical Installation, Fire Protection', Part D 'Materials and Welding', Part E 'Additional Class Notations'. Part B, 'Hull and Stability', contains design loads and scantling criteria for yachts made of steel, aluminium, FRP and wood.

Chapter 1 deals with general definitions, outfitting, equipment, tanks, loads and rudders. The loads are subdivided into overall global loads and local loads, both static and dynamic. For each construction material RINA Rules give a specific chapter. The rules are valid for steel vessels up to $120\,m$ in length and aluminium vessels up to $90\,m$ in length. For yachts with greater lengths reference is to be made to RINA Rules for the Classification of Ships. For steel and aluminium vessels (Chapter 2 and 3 respectively) a comprehensive treatment of mechanical characteristics of materials and welding procedures is presented. Design stresses and buckling criteria are defined together with many joint and construction details and reinforcements. Plating and internal scantlings are provided for bottom, sides, decks, bulkheads and superstructures. Minimum plating thicknesses are calculated by a couple of formulas as a function of design pressure, stiffener spacing and material coefficients. For reinforcements, the minimum section modulus is calculated by formulas depending on the usual parameters such as design pressure, reinforcement span and spacing and material coefficients. Different sets of formulas are available for transverse and longitudinal hull structure.

Chapter 4 is devoted to the mechanical characteristics of composites with different types of reinforcements, resins and core materials for sandwich technology. A table with formulas for determining mechanical characteristics of FRP as a function of glass content in weight is provided. Plating and reinforcement scantling procedures, valid for monohull vessels up to $40\,m$ and catamarans up to $35\,m$ in length, are similar to those already presented about steel with, in addition, a specific section about sandwich structure scantling. Structural adhesives are considered as well at the end of this chapter.

Besides the six classification societies accepted by MCA LY-2 there are other CS taking into consideration motor yachts in their rules. *Korean Register (KR)* Rules and guidance for yachts in general can be found in 'Guidance for Marine Leisure Ships' (2011) which replaces 'Rules for the Classification of FRP Yachts' (2010). This guidance is applicable to leisure boats and yachts of lengths between $2.5\,m$ and $24\,m$ in mono-hull, catamaran and trimaran hull types. Steel, aluminium-alloy, wood and FRP are considered as construction materials and design pressures are detailed for ships with/without sails respectively in this guidance. Other issues about yacht structures are contained in 'Rules for the Classification of FRP Ships' (2011) and 'Rules for the Classification of Steel Ships, Part 10: Hull Structure and Equipment of Small Steel Ships' (2011).

Hellenic Register of Shipping (HRS) Regulations for motor yachts are contained in 'Rules and Regulations for the Classification and Construction of Small Craft' (2004) applicable to wooden boats up to $36\,m$ in length, steel and aluminium vessels up to $60\,m$.

Nippon Kaiji Kyokai (NKK) Rules do not specifically take into consideration motor yachts. Guidance for yacht structure scantlings can be found in the 'Rules for the Survey and Construction of Ships of Fibreglass Reinforced Plastics' (2011), 'Rules for High Speed Craft' (2011) and 'Rules for the Survey and Construction of Steel Ships, Part CS: Hull Construction and Equipment of Small Ships' (2011).

4 DESIGN LOADS AND ASSESSMENT METHODOLOGIES

As described in the Chapter 2, the term 'motor yacht' covers practically the entire range of possible vessel types, from $10\,m$ to over $160\,m$ megayachts. Hence, there is a correspondingly large diversity in the relevant important structural loads and how they are estimated, depending on the size, type, speed, displacement or planing regime etc of vessel considered.

There is little literature concerning the loads on motor yachts specifically, since in terms of loads the fact that the vessel is a yacht often does not significantly change the loads to which it will be subjected to, with respect to conventional ships. Also, most of the research carried out concerning yachts is of a commercially sensitive nature and hence is not published. However, there are a few helpful references directly concerning yachts, and these will first be briefly described below. Following this, other work concerning the loads on high speed craft or ships, and which are also applicable to motor yachts will be outlined.

In the final section a brief description of the current rules directly applicable to motor yachts in terms of loadings will be made. However, it must be remembered that, especially for larger yachts, reference to the relevant 'Ship' or 'High Speed Craft' rules may also be required, but these rules fall outside the scope of this report, and hence are not described here (except where specific reference are made to 'yachts').

4.1 Loads on Motor Yacht

An effective subdivision of the overall loads on a motor yacht is reported by Verbaas and van der Werff (2002). They consider primary loads acting on the hull girder as a whole, secondary loads acting on large components such as decks and bulkheads and tertiary loads which affect local areas only. Primary loads consist of still water and wave induced bending moments, and torsion moments together with related shear forces. Rigging loads, in the case of sailing yachts and the loads derived from haulage operations can also be considered as primary loads. Secondary and tertiary loads, most important for the local strength evaluation, are represented by bottom and bow flare slamming loads, green sea loading and cross deck slamming for multi hull vessels. Impact loads against floating objects, or grounding loads belong to the same class of loads. As far as thermal loads are concerned, their classification depends on the extension of the area over which they apply. In the same paper the authors caution that other loads such as cargo loads and sloshing loads should not be neglected.

As stated by Marchant (1994), for smaller yachts with a length of less than $35\,m$, the structure is dominated by secondary and tertiary loads, particularly bottom and bow flare slamming, caused by the planing regime in which this type of vessels often operates. In the case of larger vessels primary loads, although combined with local loads, become predominant.

In fact, the length at which global loads become important for displacement, steel motor yachts is estimated at between 50 and $90\,m$ dependent on vessel type and usage (Roy *et al.*, 2008). A very practical and comprehensive guide of how to identify the point (in terms of vessel size) at which global buckling loads should be considered for FRP motor yachts is given by Loscombe (2001).

The global loads which become significant for larger yachts are not significantly different from those acting on ships from a structural point of view, explaining why the literature concerning global loads on large motor yachts specifically doesn't exist. In fact, as highlighted by Roy (2006), owing to the continuous increase in average yacht size the trend in this regard is to employ design and construction technologies already developed in the commercial shipping industry. Hence, the literature found concerning loads on motor yachts specifically almost exclusively concerns tertiary loads, of which most are hydrodynamic loads.

The basis of planing theory and local pressure estimation for high-speed craft has been very well documented elsewhere. The classical works of Von Karman (1929) and Wagner (1932) on water impact problems in the early twentieth century provided the background for later studies, such as that of Du Cane (1956), Heller and Jasper (1961), Savitsky (1964), Savitsky and Brown (1976), Allen and Jones (1978) leading to practical prediction methods that could be used by designers of high-speed craft to determine impact loads. In these works, mainly addressed to fast, small size motor boats, design loads are provided as slamming pressures derived by vertical acceleration measured on real scale tests. Assuming the boat dynamic behaviour like that of a rigid body, the longitudinal and transverse distribution of the vertical acceleration is calculated with respect to the centre of gravity maximum acceleration. It is then possible to determine the local pressure to be applied to the structural elements of bottom and sides in whatever position with respect to the centre of gravity.

Kaplan (1992) presented a comprehensive review of the state of the art of load calculation methodologies relevant to small and fast boats. Koelbel (1995) in his paper describes the materials used for fast boat construction and presents a complete history of structural design where all the reference theories for load calculation are listed and an alternative method for calculating design acceleration is suggested. A more practical approach to structural design of fast motor craft is given in Koelbel (2001). An assessment of planing theory for smaller craft in general is comprehensively described in many books such as those by Du Cane (1974) and Payne (1988).

The tension-compression, bending and shear loads on a $5.70\,m$ motor boat were obtained through full-size drop tests by Baur *et al.* (2004) in order to evaluate the response of the adhesively bonded construction used. The obtained data was to be used to improve laboratory simulation of service loadings of boat structures.

Rees *et al.* (2001) describe the development of a finite element code (HydroDYNA) which couples hydrodynamic and structural models in order to predict motion histories and wave slam loadings, and its application to FEM modelling of fast motor boats, and specifically to an RNLI Trent Class Lifeboat.

Santini *et al.* (2007) describe a method for optimizing hull structural design based on desired performance characteristics and expected operator manoeuvring profiles. They analyse the dynamic and transient nature of the hydrodynamic slamming of a small planing boat during drop simulations using an FSI (Fluid Structure Interaction) methodology. Slamming loads are then converted into static equivalent linear loads and input into the topology optimization software OPTISTRUCT®, developed by Altair Engineering Inc. The software, based on the finite element method, generates the best structure lay out given a package space, loads, boundary conditions and a target weight.

The problem of slamming specifically for composite ships and yachts is considered by Meijer (1996), where it is stated that whilst the approach of using extrapolated experience more than first principles for steel ships may be satisfactory, '*composite hulls at high speeds are a completely different matter*'. The impact event may produce dynamic global loads in the hull girder - bending and torsional moments and shear forces, both transient (*whipping*) and continuous (*springing*) – which are normally only considered for larger ships. However, Meijer notes that these effects may become significant for smaller craft of relatively flexible FRP. The paper itself considers only local effects induced by slamming. The importance of resistance to solid object impacts is again noted, and special caution is advised if considering carbon composites.

Lalangas and Yannoulis (1983), noting some uncertainties in existing methods for predicting the design bottom pressure, pressure reduction factors and safety factors, proposed a procedure to calculate the bottom design pressure for a $20\,m$ high-speed aluminium motor yacht. He concludes that the bottom structural design methods used were satisfactory as no failures occurred after two summer seasons of use for all four yachts.

A simplified model as a practical design tool for the time dependent calculation of slamming pressures for composite yacht panels has been developed at SP-systems (Manganelli and Hobbs 2006, Loarn and Manganelli 2010). Hull curvature effects are included, and the model was found to be in good general agreement with experimental results. However, since dynamic and hydro-elastic effects were neglected, limitations to the 2D quasi-static approach were noted, and it was thought that the range of applicability will decrease for higher impact velocities.

Most of the CS’ rules are based on the centre of gravity acceleration; the determination of this parameter by direct methods such as towing tank or full-scale tests is not so simple, especially when the yacht is large and operates at high speed. For such cases Hueber and Caponnetto (2009) present applications of CFD to superyacht design with particular reference to seakeeping computation for high speed vessels. The numerical approach is able to simulate the bow impact on waves in a heavy sea (despite the statement that the method needs to be refined). Two methods are considered, the first using a rigid motion of the hull mesh, and the other taking into account a smooth deformation of the mesh at impact. A useful time history of the vertical acceleration for two hulls with different dead rise angles is presented.

A comparison of midship plating design pressure calculated by several different methodologies is presented by Schleicher *et al.* (2003) as part of a feasibility study of an hypothetical $100\,knot$, $46\,m$ superyacht. Pressures are calculated by ABS, Lloyd’s and DNV Rules and by direct methods such as those by Koelbel (2001), Silvia (1978), Allen and Jones (1978), Heller and Jasper (1961), and Henrickson and Spencer (1982). The more conservative values are obtained using Koelbel, the lower ones from Henrickson and Spencer; with a difference of 400 % between the two. The values using the rules fall between these two extremes, at slightly higher than the average of the two.

A comprehensive series of motion and load measurements on an $18\,m$ FRP motor yacht is presented by Carrera and Rizzo (2005). The trials were particularly aimed at studying the structural behaviour of the fore part of the hull structure, which is subject to impact phenomena. The authors describe the equipments and instrumentation utilised for the tests and the attained results. The signals from pressure sensors installed on the fore part of the bottom were recorded simultaneously with signals from accelerometers and strain gauges. As well as conventional accelerometers and rate-gyro sensors, a GPS-RTK system was installed for real time monitoring of the craft motions in six-degree of freedom. Tests were carried out for different sea conditions and headings. It is worth noting that the vertical acceleration of 1g, suggested by most CS’ rules as a reference value for structure scantling, was exceeded more than once.

A systematic approach to the evaluation of design loads on rudders for high-performance boats and yachts is described by Blount and Dawson (2002), where practical methods for the evaluation of side-force, drag and torque loads are detailed.

A common structural issue (which arises from the fact that the use of a yacht is for ‘pleasure’) is that of surface finish/plate flatness due to temperature differentials between air-conditioned interiors and hot exteriors. That was often a fairly severe problem and it becames evident through discussions with shipyards and CS, but no work on this aspect has been found in the literature.

Glass structures are increasingly becoming en vogue, leading to larger glazed areas that are susceptible to wave impact or green water loads. Design loads on yacht glazing have been traditionally regulated by standards and conventions which are essentially a mix of a lot of empiricism and tradition with little science and hence a new standard, ISO/DIS 11336-1 (Verbaas and van der Werff, 2002) is under development in order to try to rectify this. Since glass is a brittle material, strength tests traditionally give a wide range of scatter. The existing approach therefore is to use ample safety factors that are incorporated into the design pressures, and for traditional glazing consisting of only small areas this was a prudent and workable approach. However, for larger glass structures the problem becomes more critical and the new standard aims to develop tests and test procedures to better define and control the variability in the glass properties in order to be able to reduce the ample 'hidden' safety factors included in the design pressures. Further to be considered, the properties of mounting methods which are of paramount importance for brittle materials since there is no local 'give' in the material.

An important issue for superyachts which is impacting increasingly on structural design, is the rising demand by owners for facilities to allow helicopter landings. This implies the space availability to install a platform of proper dimensions and structural strength to support the dynamic landing load and, as a consequence, strictly depends on the yacht size. In fact, just because of space restrictions, installing a heli-deck on yachts under $70\,m$ overall length is not practical. At present LY2 references SOLAS II-2 and ICAO Annex 14 of the Convention on International Civil Aviation for requirements for helicopter operations. In recognition of the increase in demand for providing helicopter facilities on board yachts, the MCA has established an advisory group to investigate and formulate requirements for these arrangement. These requirements, when accepted, will presumably be incorporated into LY2. On this subject some CS, such as Lloyd's Register and ABS are developing their own rules.

4.2 General Loads Publications also Applicable to Motor Yachts

Since it already provides the most comprehensive source of information on ship structural issues, one of the best sources of information for the many different types of loads that may be applicable to yachts is that of previous ISSC reports. For larger, displacement motor yachts, the various 'Loads' reports will be most informative, whilst for faster, usually smaller, semi-planing and planing motor yachts the 'Weight Critical Structures' and 'Design of High Speed Vessel' reports are extremely relevant. Table 1 summarises where the various relevant different info can be found.

It is not possible to comprehensively cover all recent work relevant to high-speed craft here, but some relevant publications are now mentioned. Books for a comprehensive overview of the subject have been written by Faltinsen (2005), and Lewandowski (2005).

The ABS 'Guidance notes on structural Direct Analysis for High-Speed Craft' (ABS, 2011) provides instructions for the 'first principles' evaluation of loading conditions and load cases, wave loads, external pressures, slamming loads, internal tank pressures, and acceleration and motion-induced loads. Guidance is also given with respect to the loadings used for finite element modelling. Kim *et al.* (2008), discuss recent developments at ABS to revise the requirements for slamming loads on high speed naval craft.

Table 1: Committee reports detailing loads in previous ISSC reports

Type of loads	1991	1994	1997	2000	2003	2006	2009
Global Loads:							
Hydrostatic loads	L	L8					
Wave Loads		L2	L2	L2	L2	L2.1, L2.2	L2, L3.4
Wind Loads		L6	L5	L2	L2	L2.7	
Ice Loads		L7				L2.6	L3.3
Fatigue							L7, IPL3
Local loads:							
Slamming		L4	L4	L 4.1	L4.1	L4.1	IPL2
Green water		L4		L4.2	L4.2	L4.3	IPL5
Sloshing		L5	L4	L4.3	L4.3	L4.2	L3.5, IPL4
Object Impact		WCS3.3		HSV6	HSV5.5		
Collision & Grounding			CG3		CG3, CG4	CG2	
Model & Full Scale Tests:					L6	L2.3	L3, L5, IPL2, IPL4
Probabilistic/ Uncertainty modelling			L6		L5, L6	L5, L6, CG3, CG4	L5, L6
High Speed Craft		WCS2.1		HSV4.3, HSV5, HSV9	HSV2.2, HSV3	L2.4	

L: Loads, IPL: Impulsive Pressure Loading, WCS: Weight Critical Structures, HSV: High Speed Vessels, CG: Collision and Grounding. Number refers to report Section.

As part of the 'Comparative Structural Requirements for High Speed Craft' the SSC-439 Ship Structure Committee (2005) compare the calculations of design loads (vertical acceleration and design pressures) made by the relevant societies (IMO, ABS, DNV, UNITAS, LR and NK).

The 'Hydrodynamic Pressures and Impact Loads for High Speed Catamaran / SES Hull Forms' is the subject of the report of another Ship Structure Committee (Vorus, 2007), and illustrative sample unsteady hull pressure distributions on a $10\,m$ bi-hull SES are given in Vorus and Sedat (2007).

Slamming loads on large yachts must be considered with care, especially for high speed vessels; the paper by Dessi and Ciappi (2010) presents a comparative analysis of slamming events and induced whipping vertical bending moment carried out on data collected with towing tank tests using segmented flexible models to allow a correlation between slamming and whipping response. Despite the fact that the work is relative to a passenger ship and a fast ferry, the results relevant to the latter case study can be utilised for large yachts, where the speed, dimensions, and the hard-chine hull form are very similar.

Much recent work concerning loads on planing craft, especially with respect to wave loads and slamming has been carried out at KTH Royal Institute of Technology Naval Architecture (Rosén 2004, 2010; Burman *et al.*, 2010; Garme *et al.*, 2010).

Finally, the goal of the ongoing Ship Structure Committee (SR-1470, not yet available) concerning the 'Structural Load Prediction for High Speed Planing Craft' is *to develop* *and verify a practical method to use time domain simulation to drive structural design of high speed planing craft.*

4.3 Motor Yacht Loads in Rules

In terms of rules, the most important demarcation is that between 'small' and 'large' yachts and generally (although not exclusively) a length of $24\,m$ is the value taken as the limit between the two definitions of size.

4.3.1 Superyachts

As described in Chapter 3 the 'industry standard' for large yachts is the MCA LY2 and in terms of the load assessment, the relevant information here is simply that, for unlimited operation, all vessels must be classed by any of the six CS listed in Chapter 4. Classification may be requested as a 'Yacht', a 'High Speed Craft' or a 'Ship', but in the present treatment only the CS' rules where specific reference to a 'yacht' is made will be considered. In the following subsections the relevant rules of each CS are briefly outlined in terms of how they define, assess and allow for the definition, calculation and application of the various design loads. As a matter of fact the equations used are generally semi-empirical in nature, with bottom pressure calculations for fast craft usually based on the approach of Heller and Jasper and Allen and Jones (Marchant, 1994).

American Bureau of Shipping (2000) refers to design loads in Section 8 in terms of design pressures, where they are considered separately for semi-planing and planing crafts and for displacement vessels. For fast vessels hydrodynamic and static pressures are defined for the bottom, side, decks and bulkheads. Hydrodynamic pressure on the bottom structure is provided by a formula containing (besides displacement, length and breadth) vessel speed, deadrise angle and a service dynamic factor representative of the acceleration at the centre of gravity. The vessel location is accounted for by a vertical acceleration distribution factor. Static pressure depends on moulded depth only.

For displacement craft with a maximum speed in knots of less than $2.36 \cdot L^{0.5}$ (L in metres) the design heads for bottom, sides, decks, deep tanks, watertight bulkheads, superstructures and deckhouses are given in a table in Section 8.3.

Hydrofoils, air cushion vehicles, surface effect craft, and multihull vessels are considered in Section 8.5. The design pressures for shell, bulkheads and decks are to be not less than those for semi-planing and planing craft. This section also states that, *Design calculations for the external design pressures due to sea loading for the various operational modes and for structures peculiar to the vessel type such a hydrofoil struts and foils etc, are to be submitted to ABS offices for review.*

The 'Design Pressures' are then used to give the hull scantlings for 'High Speed Craft' (max speed, in knots not less than $2.36 \cdot L^{0.5}$, L in metres), and the 'Design Heads' used to give displacement craft hull scantlings.

In Section 11 ABS Rules take into consideration a minimum hull girder section modulus at amidships varying with length, breadth and block coefficient. This formula applies to yachts for which the beam of the vessel is not to be greater than twice the depth. If the yacht speed exceeds 25 knots ('High Speed Yachts') an additional formula has to be applied in which the displacement and vertical acceleration at centre of gravity and at the forward end are considered.

For yachts aiming at sailing in arctic waters, a specific 'Ice Class Yachts' has been introduced by ABS. This Class takes into account different ice characteristics, such as ice cover, age and expected thickness, and type of navigation (independent or escorted by ice breaker). From the structural point of view ice navigation requires an increase in thickness for plates straddling the waterline, reduced frame distances and special material grades. The structural component must be dimensioned by a design ice pressure calculated as a function of vessel displacement, installed power, geographical position and hull shape.

Bureau Veritas (2012) design loads are provided in Part B, and in Chapter 4 an helpful table synthesises the assessed kinds of loads and where each of these may be found in the rules. Such loads are not to be amplified by any safety factor, this being already considered in admissible stress levels given in detail for each material in the relevant section. Rules also states that the wave induced and dynamic loads defined correspond to an operating life of the vessel of 20 years.

Vertical accelerations resulting in slamming phenomenon on the bottom area are dealt with in Part B, Chapter 4, Section 3 for high speed motor yachts ($V\,[kn] \geq 7.16 \cdot \Delta^{1/6}\,[t]$). These should be defined using the designer's model or full-scale tests, or lacking this via an apparently semi-empirical generalised equation. In the case that the designer does not provide the vertical acceleration, a simple formula dependant on length, the type of motor yacht (Cruise, Sport or with specific equipments) and the navigation zone is stated. Maximum admissible accelerations are also stipulated. For slow speed motor yachts no acceleration calculations are required.

As far as global loads are concerned, in Chapter 5 for steel and aluminium and in Chapter 7 for composite vessels still water and wave bending moment and shear forces are calculated as a function of hull dimensions, block coefficient and wave length and height, but only when one of the following situations occurs:

- length greater than $40\,m$;
- sailing yachts with significant mast compression or rigging loads;
- large deck openings or significant geometrical discontinuities at bottom or decks;
- transverse framing;
- decks with thin plating and widely spaced secondary stiffeners.

For multihull vessels a formula to determine the wave torque moment in a quartering sea is also provided. The manner in which the global loads should be combined is described in Chapter 5, Section 2 depending on whether the yacht is motor or sail, and mono- or multi-hull.

Local loads are defined in Chapter 4 Section 3 as hydrodynamic loads and bottom slamming loads. Hydrodynamic loads are represented by a sea pressure which is a combination of hydrostatic pressure and the pressure induced by waves. Sea pressure on the bottom and side shell is provided as a function of the navigation coefficient 'n', the full load draught, the wave height and a wave load coefficient X_i depending on the longitudinal location and on the type of yacht. The hull is longitudinally subdivided into 4 areas, for which the X_i coefficient has an increasing value from aft to stern. Impact pressure (wave impact load, distributed as a water column of $0.6\,m$ diameter) on the side shell is also calculated both for monohulls and catamarans. Sea pressure on decks is provided by tables for exposed decks, accomodation decks and superstructures decks.

In the same chapter the bottom slamming pressures for high speed motor yachts of both mono and multihull type are given as a function of the design vertical acceleration a_{cg} (defined in Chapter 4) by a relationship containing the significant wave height, hull deadrise, ship speed and other geometrical characteristics of the vessel.

Det Norske Veritas loads for 'High Speed, Light Craft and Naval Surface Craft' (2011) are assessed in Chapter 1 of Part 3 for both HSLC yachts (with speed greater than $25\,knots$) and LC yachts (speed less than $25\,knots$). Loads are subdivided into local loads, represented by slamming pressures and sea pressures, and global loads.

To calculate slamming pressures formulas are provided to determine vertical and horizontal acceleration. Design vertical acceleration (at the centre of gravity) is calculated relative to yacht length, speed and an acceleration factor (fraction of g_0) defined as a function of type and service notation, and service area restriction notation. Horizontal accelerations, both longitudinal and transversal, are also provided as a function of the same parameters defining vertical acceleration.

Dynamic pressures on the bottom, forebody sides, bow and flat cross structures are then calculated by formulas containing, besides the design acceleration, a longitudinal distribution factor, the yacht displacement and the number of hulls, unsupported panel areas, draft, maximum design vertical acceleration and deadrise angle along the hull. Sea pressures acting on the craft's bottom, side and weather decks are calculated separately for load points below and above the design waterline as a function of the vertical distance from the waterline to the considered load point, yacht draught and a wave coefficient. The pressures from liquids in tanks and the loads from dry cargoes, stores and equipment and heavy units are also taken into account.

As for other CS' rules, hull girder global loads considered by DNV consist of hogging and sagging bending moments and shear forces expressed as a function of yacht dimensions and wave coefficient. For twin hull vessels the loads on the transverse connecting structures are also addressed: vertical, transverse and pitch connecting moments are provided by formulas containing displacement and design accelerations at centre of gravity.

In the *Germanischer Lloyd's* Rules for 'Special Craft' (2003), design loads for steel and aluminium yachts of less than $48\,m$ are contained in Section 2.D for speeds lower than $7.2 \cdot \nabla^{1/6}$ (where ∇ is the moulded volume in m^3). Design pressures are calculated on hull, weather decks, superstructure and deckhouses, accommodation decks, bulkheads and tank structures. As an example, the hull pressure formula contains the ship scantling length, draught, deadrise angle, panel span and size factors, hull longitudinal distribution factor and range of service. Design pressures on decks and superstructures are determined by similar formulas but with less parameters. For speeds higher than $7.2 \cdot \nabla^{1/6}$ yachts are considered 'high speed' motor yachts and for design loads and scantling requirements reference should be made to the High Speed Craft code (GL Rules Part 1 – Seagoing Ships, Chapter 5 – High Speed Craft). The loads for yachts of less than $48\,m$ constructed of composite materials are given in Section 2.E with the same philosophy applied as for steel yachts.

Steel and aluminium yachts with length greater than $48\,m$ are briefly considered in Section 2.G, in the sense that it states that for speeds higher than $7.2 \cdot \nabla^{1/6}$ reference should be made to GL Rules Part 1 – Seagoing Ships, Chapter 5 – High Speed Craft, Section 3. For lower speeds GL Rules Part 1 – Seagoing Ships, Chapter 1 – Hull Structures should be applied.

Lloyd's Register (2011) design load criteria are considered in Part 5 of the SSC Rules. Generally the cases of displacement and non-displacement, and mono-hull and multi-hull are considered separately throughout. Chapter 1 states that '*load and design criteria are to be supplemented by direct calculation methods incorporating model tests* *and numerical analysis for novel designs*', and details on the allowable direct calculations and instructions for model experiments are then given in Sections 2 and 3 respectively.

The LR philosophy consists of considering local strength and global strength according to the 'rule length', L_R of the vessel (L_R being between 96 and 97 % of the waterline length) as follows:

- for vessels with a rule length of less than 50 m, global strength assessment is not mandatory, and only local strength should be taken into account;
- for vessels with a rule length equal to or greater than 50 m and up to 70 m, consideration of both the local and global strengths is mandatory;
- for vessels with a rule length of over 70 m and up to 150 m, in addition to consideration of local strength, a global strength evaluation is to be carried out either using parametric formulae or using direct calculation methods (3D FEM models).

Local design loads (Part 5, Chap. 2) are expressed as static and dynamic pressures acting on different part of the vessels for non-displacement and displacement craft (Part 5, Chapter 3 and 4 respectively). After 'motion response' determination (relative vertical motion and acceleration), the rules provide 'Loads on the shell envelope' (hydrostatic and hydrodynamic wave pressures, pressures on weather and interior decks), 'Impact loads' (impact pressure for displacement, non-displacement and foiled or lifting device craft, forebody impact pressure for displacement and non-displacement craft), loads on 'Multihull cross-deck structure' and the 'Component design loads' (deckhouses, bulwarks and superstructures, watertight and deep tank bulkheads, pillars, deck area for cargo, stores and equipment). Design values are synthesised in tables for mono-hull, multi-hull and components as a function of local design factor and criteria representative of hull notation, service area, service type, craft type and stiffening type.

Global loads are divided into two categories: hull girder loads, and primary loads for multi-hulled vessels. Hull girder loads are to be considered for strength purposes and distinguished on the basis of their frequencies as follows:

- still water bending moments and associated shear forces arising from mass distribution and buoyancy forces, to be calculated directly as a function of load condition;
- vertical wave bending moments and associated shear forces arising from low frequency hydrodynamic forces;
- dynamic bending moments and associated shear forces arising from high frequency bottom slamming;

Wave bending moment and slamming bending moments are provided by equations as a function of rule length L_R, breadth B, service group coefficient and block coefficient. Primary loads for multi-hull craft arise mainly from the interaction between the hulls and waves.

Registro Italiano Navale (2011, 2011a) design loads are defined in Part B, Chapter 1, Section 5. First design accelerations are defined as the vertical and transverse accelerations at the centre of gravity. Then local loads are defined as hull pressures on the bottom, side and decks for planing and displacement yachts; the differentiation between the two categories depends on whether the relative speed $V/L^{0.5}$ is greater or less than 4 respectively.

For planing vessels sea pressure should be assumed as the higher of two values obtained by the following different formulations:

- hydrostatic pressure depending mainly on yacht length, full displacement and local draught and longitudinal position;
- hydrodynamic pressure defined as a function of the yacht length, maximum design vertical acceleration, longitudinal position and other coefficients taking into account varying deadrise angles along the hull and unsupported panel areas.

In the case of displacement yachts only the first, static pressure formulation is considered.

Global loads are given in Chapter 1, Section 5 as longitudinal bending moment and shear force in still water and in waves by formulas as a function of hull dimensions, block coefficient and a speed coefficient. A direct procedure to take into account the increase in bending moment and shear force, due to impact loads in the forebody area, for the sagging condition only, is available. In this case the vertical acceleration at LCG given by the rules should be considered, which corresponds to the average of the $1\,\%$ highest accelerations in the most severe sea conditions expected. For twin hull yachts transverse bending moment and shear force and transverse torsional connecting moment are also given. The minimum section modulus of the midship section is intended to comply with the maximum total bending moment and with the maximum allowable bending stress of the material.

4.3.2 Small Yachts

For small motor yachts with length less than $24\,m$ to be commercialised in Europe, the vessel's hull should be constructed according to the ISO 12215 (2005). With respect to loadings, the relevant parts are contained in ISO-12215 Part 5 (2004) which contains detailed sections for calculation of design pressure for motor and sailing craft. All parts of the vessel are considered such as bottom, sides, decks, superstructures and deckhouses, windows hatches and doors. The bottom pressure, as an example, is calculated by a formulas as a function of the displacement, waterline length, breadth, corrections for longitudinal position x/L_{WL}, the size and aspect ratio of the shell panel and a dynamic load factor which takes into account whether the craft is displacement, semi-planing or planing (as well as whether the craft may be entirely clear of the water for short or long periods of time) given in both parametric equation and tabular form.

Harzt (1998) gives a background to the development of ISO 12215, discussing and explaining the decisions made with respect to design pressures in general and also side and deck pressures specifically. He states that the bottom pressure calculations are based on the Heller and Jasper (1961) and Savitsky and Brown (1976) approaches, and also discusses the origin of the estimates for speed, running trim angle and longitudinal impact factor and design category factor. In Appendix III, Hartz includes comparisons of bottom pressures obtained using various existing rules (VTT, BV, LR, GL, ABS) and notes that '*the load assumptions are differing considerably, which is not surprising, as the step from loads to scantlings is not identical*'.

The GL Rules for 'Special Craft - Yachts and Boats up to $24\,m$' (GL, 2003) also consider smaller yachts and boats ($6\,m \leq L \leq 24\,m$). Basic principles for load determination are given in tabular form in Section 1, A 'Hull Structures' 1.9. Hull loadings are presented for shell bottom and shell side, as well as 'correction factors for speed' for shell bottom and side and various internal structural members and frames, and then deck and superstructure loadings are specified. Rudder force and torsion moment design loadings are calculated in Section 1, A 'Hull Structures' 3.2.

Further, the RINA 'Rules for the Classification of Pleasure Yachts' (2011) can be used for smaller vessels, since their applicability is valid for yachts down to 16 m in scantling length.

5 STRUCTURAL STRENGTH AND RESPONSE

Following the practice for conventional ships, there are two design philosophies for yacht structural design that can be assumed, namely the 'first principle' approach and the use of CS' rules; often a mixture of both methods is practiced. Designing by CS' rules provides reliable scantling procedures and widely accepted loads but it doesn't allow the refinement of structural dimensions and weights. For larger, innovative and more performance sensitive vessels, a first principle approach becomes mandatory. Being based on direct calculations, first principles approach requires rigorous procedures and accurate prediction of the loads acting on the hull structure but it allows the determination of any kind of structural response for subsequent processing. The response of hull structures to different types of loadings results in static stresses and deformations, dynamic stresses in way of vibration, noise and slamming impacts, thin plate buckling and fatigue phenomena.

5.1 Structure Design Methods

The design criteria of motor yacht hull structures are mainly related to their dimensions and speed. For smaller, high speed yachts the structure scantling is mainly performed on a local basis by applying dynamic pressures stemming from planing effects, such as bottom and side slamming. For larger displacement, or semi displacement vessels, the evaluation of hull girder global strength must be performed as well, with respect to both still water and wave pressure distribution.

In most cases the first, rough scantlings are performed by the application of CS' rules. In the next iteration, a significant reduction in structure dimensions can be pursued by recourse to direct methods based on beam and plate theories. For smaller vessels direct analysis is addressed to local areas such as decks, sides or bulkheads modelled by two-dimensional grillages or orthotropic stiffened plates (e.g. Maneepan *et al.*, 2006 and Sobey *et al.*, 2009); transverse sections can be analysed by two-dimensional frames. A check of longitudinal strength can be carried out as well by simply verifying the main section inertia. This is important for FRP yachts, even if below 50 m in length, because of the low elastic modulus of the material (Loscombe, 2001).

For larger units, where global loads became predominant, the longitudinal strength is carefully evaluated by simplified two-dimensional hull girder schemes with constant or variable sections. By determining the balance between sectional weight versus sectional buoyancy it is then possible to achieve still water shear force and bending moment distributions. Additional contributions to shear and bending moments from waves can be accounted for by CS' rules or by quasi-static equivalent wave analysis. Moreover the torsion moment can be addressed from class rules. By this approach it is possible to achieve additional information relevant to structure deformations, increasingly important for verifying window glass integrity. Generally the first scantling iteration for a superyacht considers deformations rather than stresses; a realistic limit for maximum vertical deformations amidships is 1/1000 of the scantling length.

At present the structure of a medium size motor yacht produces a very complex lay out owing to the necessity of reducing the reinforcement dimensions to internal volumes' advantage, to the presence of large transom and side doors and terraces and to the increasing structure irregularity to match interior arrangements. Large openings, in particular, induce high stress concentrations and, in this regard, the analysis by numerical models has become mandatory. FEA represents the most detailed level of approach for structural design and it allows to model the structure with any detail, to keep into account asymmetrical structure such as partial decks, longitudinal bulkheads and side doors, and to analyse the structure in its three dimensional form under the contemporary action of different loadings. A review of numerical techniques now available to industry for superyacht design is presented by Köhlmoos and Bertram (2009). FEM methods for static and dynamic analysis are the base for vibration, noise, fatigue strength and ultimate strength assessment. An example of FEM analysis on a large steel motor yacht to control structural deformations and their compatibility with surface fillers is presented by Fincantieri (2010). Using a global analysis the dynamic behaviour of the yacht excited by short wave loads has been determined to quantify the dynamic vertical bending moment and springing phenomena. Then the effects of local slamming have been studied on a hull portion modelled by a very refined FEM model to determine the long term maximum displacement of side and bottom panels.

A similar approach is described by Motta *et al.* (2012) to investigate the stress distribution on a 60 m steel yacht with large side doors and other asymmetrical structural components. Particular care has been dedicated in creating the numerical model, shown in Figure 5, in order to obtain a very refined mesh capable of analysis in the time domain. The numerical analysis is still underway and the results will be compared with tests already carried out in real scale on the same yacht.

The needs of a FEM analysis is particularly felt for multihull vessels for which simplified models based on longitudinal symmetry cannot be used. An example of a FEM application to a catamaran motor yacht is presented by Luco *et al.* (2002). The study is further complicated by FRP hull material: the material properties have been verified by laboratory tests and then modelled by proper multilayer elements. The authors considered three static loading conditions typical of multihulls: hydrostatic pressure, prying moment and torsion, all provided by DNV Rules for high speed crafts.

The present trend in structural design is to perform combined FEA/CFD investigations where pressure distributions resulting from seakeeping analyses are directly applied to a FE numerical model. Such a procedure is compared by Hermundstad and Wu (1999) with a traditional global load method and with a modal method, all applied to a monohull and a catamaran fast vessel.

Superyachts have very large superstructures in order to allow for more interior space; when the superyachts dimension exceed 100 m in length the interaction of superstructures with hull structures should be considered with care. Albertoni *et al.* (2000) made an investigation on this subject modelling a 70 m naval vessel and analysing the contribution of superstructure in terms of stress and deformations. From the analysis,

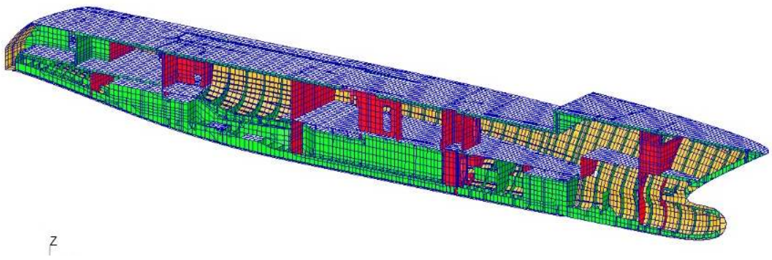


Figure 5: FEM numerical model of a 60 metres superyacht.

for long superstructures, 1 or 2 expansion joints become mandatory in order to keep deck stresses within acceptable values.

5.2 Vibrations and Noise

Vibrations and noise are crucial topics for superyachts and they require detailed calculations from the earliest of design stages to verify the dynamic behaviour of hull structures and their response to exciting loads such as propellers, engines and wave encounters. Even if vibrations and noise are more critical for metallic yachts, FRP units are not immune from these phenomena. The problem is increased by higher comfort requirements and constraints imposed by the ISO 6954 (2000) with respect to the previous ISO 6954 (1984) standard, together with CS notations which ask for even lower levels of vibration and noise. All main CS recently introduced comfort requirements addressing highest admissible vibration and noise levels. Baker and McSweeney (2009), as an example, present a complete analysis of present ABS Rules concerning vibrations and noise published in the 'Guide for the Class Notation Comfort - Yacht' (2008). Two notational options are considered: COMF(Y), which establishes a level of comfort based on ambient noise and vibration alone and COMF+(Y) which adds slightly more demanding criteria for noise and vibration, and provides additional criteria for the assessment of motion sickness. ABS Yacht Comfort guide, however, have been recently revised in some aspects. In Table 2, a synthesis of the new version is reported for yacht below and over $45\,m$ in length. Comfort regulations for yachts are also contained in other CS rules such as:

- Bureau Veritas (2011) Part E, Section 5, 'Additional Requirements for Yachts';
- Det Norske Veritas (2011), Part 6, Chapter 12, 'Noise and Vibration';
- Germanischer Lloyd (2003b), Part 1, Chapter 16, 'Harmony Class';
- Lloyd's Register (2011), Chapter 6, 'Passenger and Crew Accommodation Comfort';
- RINA (2011a), Part E, Chapter 5, 'Comfort on board'.

Some examples of maximum vibration levels are reported in Table 3 for BV, LR and RINA.

From the structural point of view vibrations take place both at global or local level, being the first ones more incisive and difficult to put right after the yacht is built. Even

Table 2: Maximum whole-body vibration according to ABS (COMF(Y)) for yachts below and over $45\,m$ in length.

Yacht length	Notation	Frequency Range	Acceleration Measurement	Maximum Level	
				Underway	Anchor
$L \leq 45\,m$	COMF (Y)	$1 - 80\,Hz$	a_w (v)	$89.4\,mm/s^2$ $(2.5\,mm/s)$	$53.5\,mm/s^2$ $(1.5\,mm/s)$
	COMF +(Y)	$1 - 80\,Hz$	a_w (v)	$53.5\,mm/s^2$ $(1.5mm/s)$	$45.0mm/s^2$ $(1.25\,mm/s)$
$L > 45\,m$	COMF (Y)	$1 - 80\,Hz$	a_w (v)	$71.5\,mm/s^2$ $(2.0\,mm/s)$	$45.0\,mm/s^2$ $(1.25\,mm/s)$
	COMF +(Y)	$1 - 80\,Hz$	a_w (v)	$53.5mm/s^2$ $(1.5mm/s)$	$35.75mm/s^2$ $(1.0mm/s)$

a_w = multi axis acceleration value calculated from the root-sums-of-squares of the weighted root mean square (RMS) acceleration values in each axis (a_{xw}, a_{yw}, a_{zw}) at the measurement point. v = spectral peak of structural velocity in mm/s.

Table 3: Maximum whole-body vibration according to Bureau Veritas, Lloyd's Register and RINA Comfort Rules for yachts.

Location	Bureau Veritas		Lloyd's Register		RINA	
	Frequency	v $[mm/s]$	Frequency	v_{rms} $[mm/s]$	Frequency	v $[mm/s]$
Cabins and lounges	$1-80\,Hz$	1.0 – 3.0	$1-80\,Hz$	1.8 – 2.5	$0-100\,Hz$	1.0 – 3.0
Public spaces	$1-80\,Hz$	1.0 – 3.0	$1-80\,Hz$	2.5 – 3.3	$0-100\,Hz$	1.0 – 3.0
Open recreation decks	$1-80\,Hz$	2.0 – 4.5	$1-80\,Hz$	2.5 – 3.8	$0-100\,Hz$	2.0 – 4.0

v_{rms} = overall frequency weighted r.m.s. value of vibration during a period of steady-state operation over the frequency range 1 to $80\,Hz$. v = spectral peak of structural velocity.

if simplified models based on variable section girders with concentrated masses remain a valuable tool to calculate approximate values of the first natural frequencies of the hull, only by FEM analyses of the whole structure is it possible to achieve reliable results and to avoid any structure resonance with the exciting frequencies. Given that the propeller blade passing frequency is relatively low (below $10-15\,Hz$) the danger exists more probably for large units over $80\,m$. The presence of large openings, in addition, further complicates the dynamic behaviour of the hull lowering its natural frequencies and inducing additional torsion modes.

Where local vibrations are concerned, decks and superstructures are the most critical areas; most inconveniences come from high frequency excitations, primarily caused by main and auxiliary engines, and by structural discontinuities and irregularities. Also, in this case a detailed FEM analysis is the only way to individuate and correct problems. As a general rule the only way to avoid vibrations is to keep natural frequency very high and this can be achieved only by increasing hull stiffness. In this regard the longitudinal framing system shows higher natural frequencies with respect to the transverse one; this may be ameliorated by reducing the transverse frame distance and the longitudinal stiffener spacing. As a matter of fact any action towards vibration reduction implies an increase in structural weight: as an example, it has been estimated that for a $95\,m$ megayacht the weight increase to avoid maddening vibrations amounts to more than 100 tonnes.

Köhlmoos and Bertram (2009a) present a specific analysis of the vibrations induced by the propulsive system of a superyacht, performed by the combined use of experimental techniques, FEM and CFD tools. First the hull natural frequencies have been measured by an experimental investigation. In a second phase the excitation sources have been identified by a CFD analysis of the water flow around appendages and applied to a FEM model of the ship to individuate critical areas. By a series of modification of underwater after body performed by CFD simulations and correspondent FEM control of vibration levels of critical areas, the problem has been iteratively solved.

The noise abatement for motor yachts is another strategic issue related to onboard comfort and most difficult to achieve because of powerful and high speed propulsion engines, related gear boxes and highly loaded propellers with reduced clearances. The acoustical implications of motor yachts should be taken into account from the earliest of design phases because any subsequent interventions on an already built unit in most cases doesn't give any improvement. A synthesis of a correct approach to noise assessment on small vessels is presented by Juras (2000); he first analyses the noise sources on board and then the possible actions to reduce their intensity. For propeller (or water-jets), noise solutions are a higher number of blades, skewed blades and appropriate propeller-hull clearance; for engines and gearboxes usual acoustical enclosures

Table 4: Maximum noise levels for superyachts. Values in $dB(A)$ are provided for 'in harbour' and 'sailing' conditions.

Spaces	Lalangas (1983)	ABS (COMF(Y))	BV	GL (cruise ship)	LR	RINA	90 m yacht (2011)
	Harb/Sail	Harb/Sail	Harb/Sail	Harb/Sail	Harb/Sail	Harb/Sail	Harb/Sail
Owner cabin	35/73	40/45	40/50	44/52	50/50	45	40/44
Guest cabins	35/73	45/50	40/50	46/54	53/53	45	43/47
Lounges	40/77	50/50	45/55	52/60	55/55	55	45/50
External decks	50/89	60/65	55/75	64/72	63/63	55	65/70

are the most used tools. Then the noise propagation paths (air-borne, structure-borne and hydrodynamic noise) are analysed together with relevant measures of noise abatement to be adopted in accommodation and working spaces. The author asserts that there are not big differences between steel, aluminium and FRP yachts in the noise dominant frequency range (up to 125 Hz) while better behaviour is shown by wooden vessels. Finally some considerations on the existing noise levels criteria are carried out, underlining that they have been established for large ships and that, for smaller vessels, the noise level on board is generally higher.

On this subject it is interesting to assess the developments of noise levels in time. Lalangas and Yannoulis (1983) report these values for a planing aluminium motor yacht in two different operating conditions: underway at full power and when at anchor with operating generators (sailing/anchor). In Table 4 maximum noise levels are compared among Lalangas (1983), ABS, BV, GL, LR and RINA comfort Rules. Finally the values resulting from real scale measurements on a 90 m superyacht built in 2011 are reported as well. To be noted is a much smaller difference between under-way and at-anchor conditions.

Nevertheless the theoretical noise prediction at the design stage still is not fully reliable. A numerical procedure based on FEM approach has been applied to a container ship by Cabos and Jokat (1998). This procedure simulates the propagation of structure borne noise in complex ship structures, taking advantage of existing finite element models created mainly for strength and vibration computations. An example of an integrated approach to this problem is presented by Colombo *et al.* (1995) for a 30 m fibreglass motor yacht. In this paper the prediction and experimental verification of noise and vibration level is described.

5.3 Buckling, Fatigue and Reliability

Buckling phenomena on superyacht structures are not so frequent but particular attention must be paid to structures made from FRP and aluminium because of their low elastic modulus. Loscombe (2001) proposes a procedure to calculate when it becomes necessary to take into consideration the buckling phenomena of panels on FRP motor yachts. Buckling stress values are provided by a simple formula as a function of glass fibre weight fraction, glass reinforcement weight and shortest span of the panel. Benson *et al.* (2009) present a detailed FEM analysis of the ultimate strength of aluminium stiffened panels built from marine grade 5083-H116 and 6082-T6 under compressive load. The paper describes a series of nonlinear large deflection FEM analyses carried out on aluminium panels typical of high speed vessel deck or bottom structures, investigating their uniaxial in plane compressive strength assuming interframe and overall collapse modes. The results have been compared to equivalent steel panel analyses.

Given the relatively low yearly usage factor of a motor yacht, fatigue life evaluation is not a limiting criterion in structural design. Nevertheless, a scrupulous designer must not ignore this aspect. The usual procedures based on cumulative damage and crack propagation theories adopted for ships are applicable to yachts as well. A complete procedure to analyse the fatigue life of a $68\,m$ aluminium catamaran is presented by Di *et al.* (1997). A complete FEM model of the vessel has been loaded by fundamental wave loading cases including longitudinal and transverse bending, torsion and splitting moments. Some cracks have been included in the numerical model in order to study the consequence of fatigue damage on the structure. Furthermore, a fatigue life assessment has been carried out by the application of S-N curves and fracture mechanics.

Reliability methods can be applied to superyacht structures as for conventional ships; an example of such an approach to the structural design of a $34\,m$, steel patrol boat is described by Purcell *et al.* (1988). The structure scantling has been carried out by traditional method and FEM calculations. Full-scale testing have been performed as well to establish a relationship between hull stress and acceleration measurements. On the base of the gathered data the probability of bottom plate yielding has been calculated by Monte Carlo simulation. The described calculation is based on an operative life of 15 years and 2000 hours of operation per year. Considering 8 hours per day, this corresponds to 250 days of navigation per year, totally out of the common run for superyachts.

5.4 Yacht Motions

Even if not strictly a structural item, the response to waves is crucial for the onboard comfort and for seasickness arising. The latter heavily influences the good or bad mood of owner and guests and a preliminary analysis of the vessel characteristics on this subject is advisable. This important issue is discussed by Dallinga and Van Wieringen (1996) in terms of comfort criteria, hydrodynamic characteristics, 'mission' related criteria (e.g. operability) and prevailing wave climate. Design indications to obtain a comfortable vessel and methods of zero speed stabilisation are given as well. Van Wieringen *et al.* (2000) extend this work using both motion simulator tests and long-term ratings for both passengers and crew. Theories of motion sickness, general operability criteria and design considerations are also presented by Stevens and Parsons (2002) for fast vessels.

6 MATERIAL SELECTION

Given that the driving philosophy in designing and building motor yachts is the cost reduction, the choice of the construction material also depends on their specific mission and dimensions. Materials are chosen for their appropriateness in the same way they are for vessels with other missions. As with commercial and government vessels, motor yacht material selection is predominantly based on cost (both initial and life-cycle) and weight. Insulation properties, predominantly noise and thermal, and vibration damping, are often emphasized. Unlike those other vessel types, some yacht materials are chosen for their aesthetic qualities.

On account of the demand protraction wooden yachts below 24 m in length continue to be built by a restricted number of long experience shipyards. In the higher range between 24 and 45 m, even if fibre reinforced plastic (FRP) is the most diffused material, aluminium alloy has a wide application, especially for high performance, one off realisations. The upper bound of this category represents the FRP dimensional limit owing to its low mechanical properties and elastic modulus; at the same time steel begins to become the standard. For vessels over 45 m global loads assume important values and steel becomes the only possible choice. Aluminium alloys continue to be an interesting alternative to steel material for high performance vessels while it is the standard for superstructure construction. A very detailed analysis of the advisable materials for high speed vessels is presented in the paper by Jackson *et al.* (1999) which can be considered a real point of reference on this subject. All the mechanical properties, including the specific strength and rigidity of various types of steel, aluminium and FRP are tabulated and compared with each other. The titanium Ti-6Al-4V alloy is considered as well.

A comparison of steel, aluminium and FRP as possible alternatives in the construction of a large motor yacht has also been carried out by Marchetti (1996) with regards to mechanical properties, fatigue life, impact strength, corrosion, vibrations and noise propagation, reparability and hull weight. A similar work has been published by Boote (2004) in which the structural scantling of a 55 m yacht has been performed for steel, aluminium and FRP construction. The three solutions have been compared in terms of shell, longitudinals and frame weights; the final comparison, made for the yacht at half load displacement showed that the FRP version had a displacement 9 % lower than the steel one, while for the light alloy version the difference rose to 17 %. The main advantages and disadvantages of each construction material are synthesised in the previous ISSC 2009 Report of V.8 Committee about sailing yachts and they remain the same for motor yachts. In this chapter current trends in material selection and the associated production methods specifically in the motor yacht industry are described.

6.1 Wood

In the last two decades a return of the oldest material for yacht building has been observed. Even if the traditional hull construction based on solid wood has become more and more difficult due to the low availability of exotic woods such as mahogany, teak, okoumé and iroko, new construction techniques based on plywood and laminated wood, coupled with new bonding products derived from the composite industry, allow the best advantages of wood's mechanical properties and light weight to be exploited. In addition modern techniques more efficiently protect and seal the wood from moisture. Mahogany continues to be the most wanted for solid parts and plywood, while red cedar is the most suitable for laminated strips. Other less exotic woods like oak, ash, elm and spearwood are used for structural components, depending on local availability. Moreover wood continues to be the basis material for refitting and repair and the most diffused material for interior and furniture on modern yachts and active research in processing techniques is continuously carried out by designers to achieve new visual effects in wood for furnishing.

6.2 Metallic Materials

The steel types used for yacht building are the same as those used for ships and are well described by the CS' rules. For displacement vessels of low/medium size dimensions, with transversely framed systems, mild steels with yield strength below 235 MPa have been widely utilised since the sixties. Then the necessity to reduce structural weight drove the use of high tensile steels with yield strengths up to 390 MPa and, at present, almost all motor yachts are built with these alloys. For vessels with high performance requirements and medium/large dimensions, aluminium is the best choice: AlMg 5083 is the typical aluminium/magnesium light alloy used for hull construction, particularly resistant to salt environment and very suitable for welding. If properly protected by sacrificial zinc anodes the problem of its vulnerability to galvanic corrosion are easily overcome. Recently, for structural parts not in contact with water, the 6000 series of alloys are successfully used because of the lower cost. As aluminium's mechanical properties are heavily influenced by welding procedures, their values are commonly provided in unwelded or welded conditions. A complete review of aluminium light alloys for marine constructions, with main characteristics and research trends is presented by Sielski (2007). Both steel and aluminium hulls suffer shell deformations caused by welding processes and reworking and/or fairing correction by filler is always required.

The use of titanium has increased recently due to the reduction in its cost and a certain interest has been devoted to this material also in the field of yacht construction. While titanium has been used in a variety of marine applications since the fifties, its cost was prohibitive for most uses (Williams, 1970). At the present time it is roughly twice as expensive as stainless steel for equivalent strength while having roughly 57 % of stainless steel's density. Grade 4 and 5 titanium are mostly used in large components under large loads, such as hydraulic cylinder rods, padeyes and cleats. Other components include exhaust components, stanchions, seawater piping, valves and ventilation components (Lazarus, 2011). Some failures have pointed out however that while the stainless parts they replaced would show small amounts of observable damage prior to failure, the titanium parts developed fatigue cracks that were easily missed, necessitating a periodic inspection process. A promising area is for titanium rudder shaft bearings due to their low corrosion.

6.3 Fibre Reinforced Plastics

After several experiments of partial fibreglass boats (aluminium frames with FRP shell) were started in the forties, the first FRP motor boat was a 41 ft sportfishing boat, built in the USA in 1959 utilising a combination of polyester resin and E-glass fibres manufactured with a hand lay-up procedure in a female mould. Since then great progress has been reached in composite technology applied to vessel construction. While E-glass fibres remain the basic reinforcement owing to their acceptable mechanical properties and low cost, for more specific applications, where higher strength and stiffness are required, together with lower weight, aramid and carbon fibres are more suitable.

As the distinct advantage of FRP composites is the ability to tailor the property directionally to suit specific applications, a very large number of fabrics have been made available on the market for glass, aramid and carbon fibres. The most used in the boatbuilding field are listed by Boote *et al.* (2006) together with their most relevant construction technologies; many issues relative to regulations and new manufacturing are contained as well.

Thus, unbalanced woven roving, with a higher fibre percentage in the warp direction, are used to increase the hull stiffness in the longitudinal direction; the use of rovimat (mat and roving stitched together) allows the lamination process to be significantly sped up. Biaxial fabrics are used to increase a hull side's resistance to shear forces and torsional moments. Unidirectional reinforcements are used on beam flanges to increase stiffener modulus keeping weight low. Where resins are concerned, isopthalic and orthopthalic polyester resins are progressively replaced by vinyl ester resins to increase the composite resistance to the marine environment, with particular reference to osmotic blistering. For particular applications with aramid and carbon fibres and when greater fatigue or impact resistance is desired, the most expensive and efficient epoxy resin is generally used. Arvidson and Miller (2001) showed the higher shear strength of the epoxies and vinyl esters allow the elimination of 'tie' layers of random-oriented mat, significantly reducing weight.

Sandwich plating, commonly used for decks and then even more often for hull sides as well, are generally built with glass fibre skins and balsa or PVC cores; various densities are available to match different resistance requirements. Where cores are concerned the best solution in terms of weight and stiffness is represented by both Nomex or aluminium honeycomb. In this case particular care is required when bonding skins and core to each other. Sandwich construction is used in place of single skin construction to reduce weight and improve vibration damping and provide greater thermal insulation. When the weight reduction becomes mandatory more sophisticated materials are used for skins such as carbon and aramid. Core selection becomes an important consideration with trade-offs for each of the popular types. Cores are often selected by their shear strengths and the strongest for its density is end-grain balsa wood. Balsa's main drawback is its tendency to rot if exposed to moisture for a long period of time, requiring careful fabrication in the boat and adherence to high quality standards during repair or modification. PVC cores are growing in use with the cross-linked varieties more appropriate for deflection limited designs and the linear PVC cores more suited for impact resistant designs. Polyurethane cores are used when insulation is a primary concern, while honeycomb cores of aramid, aluminium or polyethylene are used when reduced weight is the main goal. Honeycomb cores are often combined with thicker, 'cosmetic' face sheets for joinery.

At present environmental sustainability is becoming more and more inherent to the FRP marine constructions owing to the large quantity of material needed to build a yacht. An intense research is addressed to new materials that can be easily recycled and that can be derived from sources that are unlikely to be depleted or finite. Particular attention has been devoted to natural fibres such as flax or hemp encased within a polylactic acid resin matrix. In his paper Gravil (2011) reports a comparison between natural and glass laminates characteristics, with particular attention to mechanical properties. Malmstein *et al.* (2011) have been investigating the use of sustainable structural composites for FRP construction, in particular looking at the durability of castor oil and linseed oil based resin systems combined with glass fabric to long term exposure to water. These systems show promise in mechanical properties in comparison to epoxy/glass composites (in the case of castor oil derived resin and glass) and polyester/glass (in the case of linseed oil derived resin and glass).

7 STRUCTURAL ARRANGEMENTS

Structural arrangements of yachts show diversities in accordance with hull length, hull forms, speed range and construction materials employed. In the following the most important structural characteristics and developments are outlined for each construction material.

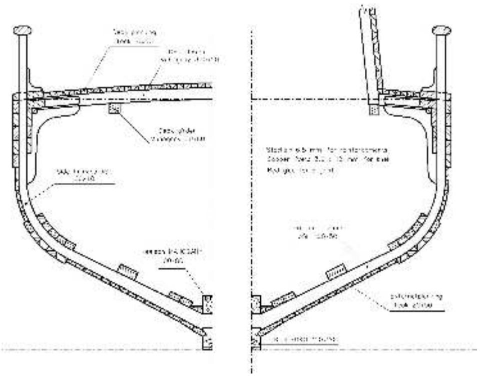


Figure 6: Typical main section of a wooden displacing boat with timber structural elements.

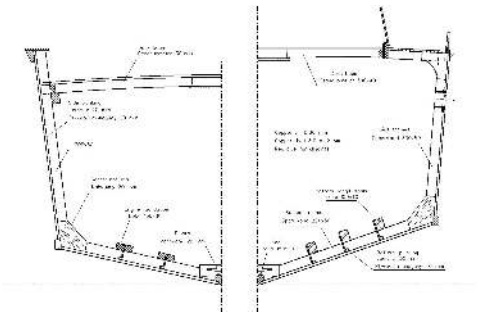


Figure 7: Typical main section of a wooden planing boat with plywood and laminated components.

7.1 Wood

Wooden boat construction is often defined as an 'art' rather than a simple profession. The solutions to work, to bend, to glue and to join solid wood have approached perfection through the centuries. The displacing, slow vessels with round hulls were built with the traditional solid technique with closely spaced frames and floors and few longitudinals, with keelsons to support engines; the low speed (often below 10 *knots*) and the reduced dimensions did not require additional longitudinal stringers (see Figure 6). The need to reduce the weight and to increase the speed though has directed builders to new solutions based on the use of plywood. With flat or single curvature bottoms and sides it became easier and cheaper to build straight frames connected by plywood floors and brackets by means of 'red glue' and copper rivets.

This solution continued to be largely used up to the Sixties to build fast patrol boats and relatively large motor yachts with just some innovations represented mainly by the introduction of glued lamellar wood. Lamellar construction allows the building of long and thick keels in a unique piece to include the required curvature. With multilayer planking, there are reduced transverse frames and, in general, a reduction in joints and structural mass, improving the craft's performance through reduced resistance. In Figure 7 an example of a main section of a 20 *m* wooden yacht is presented. From 1900 to 1970 many motor boats have been built with this technique in the United States and in Europe. A review of the present criteria and methodologies for wooden yacht construction is presented by Vesco (2005). In his paper many drawings relative to a 21 *m* planing yacht built in wood are contained together with a synthesis of rules relevant to wood scantlings and many interesting photos of the construction sequence.

Nowadays a number of shipyards continue to use wood for motor yacht construction, pushed by an increasing demand of enthusiasts of this material. The average dimensions of modern wooden motor yachts are around 20 – 25 *m* in length, but vessels up to 30 *m* are not so rare. Even recently in Dubai a wooden motor yacht has been built that measures 47.5 *m* in length and a 140 *m* wooden sailing yacht is under construction in Turkey.

7.2 Steel and Aluminium

As previously mentioned the use of steel in motor yachts coincides with the introduction of steam engines to power ships. Steel vessels at first had a typical transverse, bolted structure with close frames and longitudinal primary reinforcements with the same, well tested lay-out coming from wooden constructions. To save weight and to overcome the difficulties in assembling plates some units had wooden shells and deck planking.

This lay-out soon showed its limits with regard to speed performances because of its high weight. The definitive change in steel vessel structure came at the end of the World War II with the invention of welding, thanks to which it was possible to reduce significantly weights and costs, to increase strength and stiffness and, as a consequence, the length of ships. In addition welding made it possible to realise new and more fashionable hull and superstructure lines, this last aspect being particularly attractive for yacht designers. In its beginnings, welded large steel motor yachts were built with normal steel with a traditional transversely framed structure composed of secondary frames 500–800 mm spaced and web frames every three or four intervals. Longitudinal reinforcements were limited to one central and two or more lateral keelsons on the bottom, with reinforcements on the side and deck girders (see Figure 8). To reduce weight and improve stability superstructures were built in aluminium light alloy with riveted joints as the welding technique for this material became only reliable later in the Sixties. The hull-superstructure connection was made by screw bolts in such a way to insulate steel from aluminium and avoid dangerous galvanic action.

Nowadays a bimetallic joint is widely used consisting in an aluminium /steel strip explosively clad together. The steel side of the strip is welded to the main deck and the superstructure is welded to the aluminium side of the strip. A detailed description of the bimetallic strip concept and construction is presented in the paper by Young and Banker (2004) together with its most important marine applications.

With the increase of conventional ship dimensions hull structural lay-out moved from a transverse scheme to a longitudinal one, in order to increase the longitudinal strength and stiffness. The same trend was assumed for motor yachts where the longitudinal structure was particularly appreciated for its reduced weight.

Longitudinal framing system on superyachts is characterised by widely spaced, deep transverse frames, typically between 1000 mm, for aluminium vessels, up to 2500 mm for steel ones, depending on dimensions and speed; lower values are often assumed in the bow and stern areas to better withstand slamming and collision loads. Frames support longitudinal stringers, generally bulb or angle profiles, closely spaced (between 300 and 600 mm) to minimize shell thickness (see Figure 9).

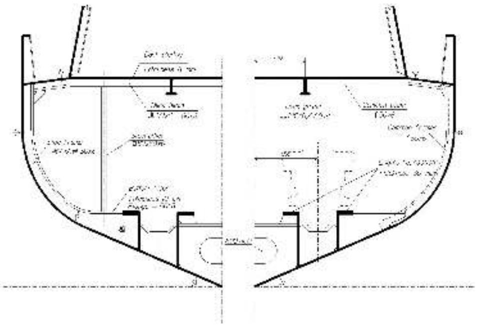


Figure 8: Main section of a displacing motor yacht in welded steel with transverse framing lay out.

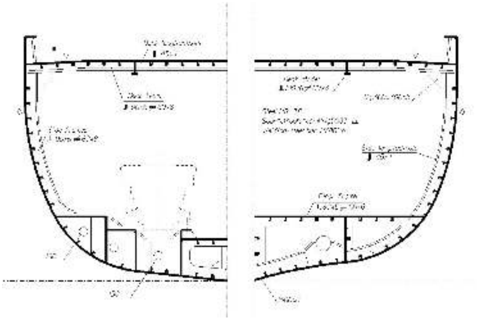


Figure 9: Main section of a modern motor yacht with longitudinal framing structure.

Longitudinal framing gives a higher section modulus without any weight increase with respect to transverse framing but, from the construction point of view, it requires higher construction times and costs because of the larger number of connecting members. For this reason, generally small yachts are built with a transverse structure while, for longer ones when hull girder loads increase significantly, the longitudinal structure is always assumed; the transition length stands between 50 and 80 m.

A third solution is represented by hybrid structure in which bottom and decks are longitudinally framed and sides are transversely framed. This lay out represents the best in terms of resistance to longitudinal bending and to side loads and it is particularly suited for yachts sailing in icy water. On the other hand a hybrid structure is the most expensive one and shipyards are reluctant to adopt it.

So far when a new design is starting, the choice of the framing system often requires a deep investigation taking into consideration strength, costs and other factors like noise and vibration. Schleicher (2003) in his paper about the 100 $knots$ super yacht, together with the main properties of suitable construction materials (high strength steel, aluminium and FRP), presents a comparative analysis of hull weights relative to framing systems. For the three considered materials the weight per metre is plotted versus stiffener spacing (from 1000 to 2000 mm) for both transverse and longitudinal framing systems. Another systematic comparison between longitudinal and transverse framing system has been carried out by Roy *et al.* (2008) on an 85 m steel yacht for which the two lay-outs have been fully developed, using the Lloyd's Register SSC Rules, for a section of hull 20 m in length. The considered length of 84 m is very close to the limit length of a 3000 GRT vessel for which MCA LY2 is still applicable. The study presents results in terms of weight, number of structural parts to be assembled and welding length. Other factors are considered as well, in particular the influence of framing system on noise and vibration.

While small and medium size yachts are fitted with only one main deck, on larger vessels (over 60 m) an intermediate deck is inserted between the main one and the double bottom. The two deck arrangement allows additional space below the cabin deck generally devoted to crew personnel, and a technical tunnel where most piping and cables can be fitted and easily inspected (Figure 10).

Present trend asks for the introduction of large openings in the hull transom and sides in order to give to cabins direct access to the external (balconies) or to allow tenders to be easily lifted and recovered into garages or to enter directly into inner harbours; on some yachts, other openings can be found at fore on the main deck for tender recovering. The presence of these large openings, often not symmetric, has a negative effect on the hull watertightness first of all, and then on the hull beam

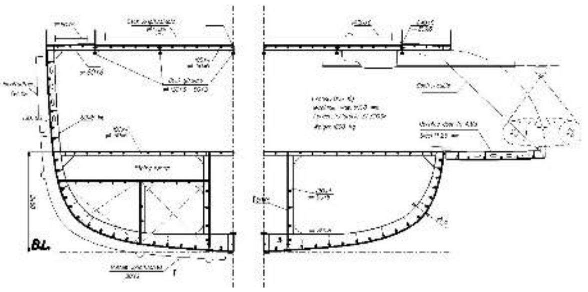


Figure 10: Main section of a 60 m steel yacht with intermediate deck and side door.

strength and dynamic behaviour; by the way they interrupt the structure integrity and continuity. For these reasons opening doors should have the same resistance of the integral hull structure and very strong closure mechanism and hinges which allow for a perfect closure and watertight are necessary. In the same way proper stiffening frames should be implemented in the hull around the opening to avoid local deformations (with consequent water entrance) and global bending and torsion effects. Door hinges should be dimensioned properly to resist to the high accelerations induced by the yacht motions in waves. To reduce inertia closing doors are built in aluminium light alloy.

As already mentioned in Chapter 5, the only way to evaluate the consequences of large openings on the structural behaviour of the hull, both statically and dynamically, is by a preliminary FEM analysis of the complete vessel. Even if the cost of hull structures for a steel yacht is about 10 % of the total price (compared with more than 50 % for a bulk carrier), an accurate scantling can have a significant positive effect on cost reduction. This is the aim of the optimization procedure presented by Motta *et al.* (2011) based on the use of the LBR 5 software and applied to a 60 m superyacht. The conclusions show a reduction of the structure weight of up to 8 % with respect to the initial design carried out according to CS' rules and direct methods.

The limit of welding, for which it was not possible to join plates thinner than 3 mm, made steel suitable for yacht having lengths in excess of 40 m. Below this limit steel can be replaced either with FRP or with aluminium light alloy. Both offer excellent results with regards to lighter displacement and aluminium is also particularly suitable for the construction of one off units or for small series production. Aluminium light alloy was originally difficult to construct due to accessible and cost effective welding technology and therefore only saw application in aerospace and in military patrol boats. By the beginning of the Sixties, the yacht industry was able to take cost advantages from the progress in TIG (Tungsten Inert Gas) and MIG (Metal Inert Gas) welding techniques. The structural lay-out of aluminium boats is not so different from steel vessels and only some restrictions should be respected, mainly due to the different mechanical characteristics and welding behaviour of this material. Where the framing system is concerned Kaneko and Baba (1982) suggest avoiding transverse structures for values of speed-length ratio, $V/L^{0.5}$, greater than 4.

Modern aluminium yachts are generally longitudinally framed with shorter spacing with respect to steel (not more than 1000 mm) and symmetric section stiffeners, such as T or flat bars, are recommended to reduce the risk of lateral buckling. Very interesting design aspects are presented by Henrickson and Spencer (1982) for an aluminium crewboat, including the bottom structural analysis based on a 'limited' reliability approach and the evaluation of the fatigue life. Another very rich information source is represented by Lalanga and Yannoulis (1983) in which the design and construction of a 25 m aluminium motor yacht is presented. They provide simple formulae to calculate bottom plating thickness and longitudinal and transverse reinforcement moduli as a function of design pressure. With this procedure a saving of about 40 % of the hull structure weight is declared by the authors. The concept of weight saving is particularly stressed in the paper by Rusnak (1999) about the design and construction of a 40 m sportfisherman built in aluminium, with a speed of more than 30 $knots$. The author writes that *in general the design philosophy for structure was to optimize the overall structure to save weight, with particular emphasis on reducing plating thickness throughout.* This was achieved by many solutions such as *lightening holes and scallops added wherever possible to reduce weight.*

7.3 Fibre Reinforced Plastics

Since its first applications, dated at the end of the World War II, FRP spread throughout the yacht industry and, in a very short time, it became the most diffused material for small and medium size pleasure and work boats. The first structural lay-out consisted in a thick, single skin shell stiffened by ‘box reinforcements’ having a longitudinal framing system with web frame interval between 1000 and 2000 mm; in Figure 11 the main section of a typical semi-planing yacht with single skin hull is shown. Reinforcements have top-hat sections (also called ‘box’, or ‘omega’) with empty or PVC cores. This latter solution is now preferred because of the advantage of a simpler construction (the PVC core works as a male mould on site) and because the empty ‘top-hat’ beams absorbed and trapped water inside. Secondary stiffener sections in FRP constructions are not smaller in scantlings as usually observed for metallic structures where the ratio of web height between secondary versus primary reinforcements must be below 0.5. In fact, while structural connections or crossing beams represent weak points in steel and aluminium structures because of welding, in the case of FRP joints and crossings the mode of construction requires glass overlapping and extra material and they subsequently become stiffer zone. This helps compensate for FRP’s low Young’s modulus and achieves higher hull stiffness, avoiding structure deformations when sailing at high speed or in rough seas. In addition the number of stiffeners is reduced, therefore reducing production cost.

Despite their ease of fabrication, top-hat-type stiffeners do not have standard cross section parameters. Tsouvalis and Spanopoulos (2003) provide design curves for tophat-type cross sections meeting specific scantling requirements and Maneepan *et al.* (2006) looked at tophat stiffener lay-up optimisation. The geometric parameters considered are the crown thickness and width, the web thickness and height, the flange width, the web angle and the flange angle. The mechanism of shear stress transfer between web and flange in FRP beams is not the same as for steel so the determination of the effective breadth cannot use the same rules assumed for steel structures; on this matter Boote (2007) made a parametric investigation using FEM models to individuate linear regressions to be used in FRP structure scantling.

The low elastic modulus of this material precluded the building of very long vessels and the effort of designers and engineers was always devoted to increasing stiffness, more than the resistance, of FRP. This task has been partially achieved by ‘sandwich’ construction, which made it possible to obtain more rigid hulls eliminating, at the same time, secondary stiffeners thus achieving a simpler and lighter structure. In addition

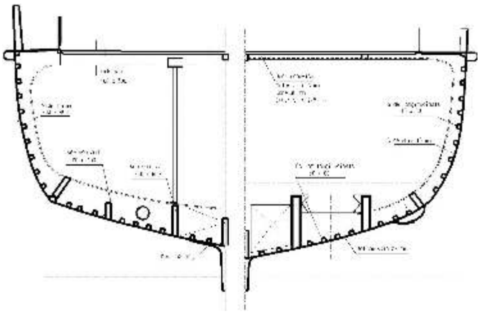


Figure 11: Main section of a 40 m FRP displacement yacht with single skin hull.

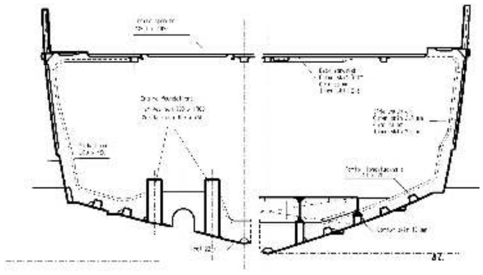


Figure 12: Main section of a 25 m FRP planing yacht with sides and deck in sandwich.

the use of more sophisticated fibres, like carbon and Kevlar, together with new lamination techniques (resin infusion and resin pre-impregnated fibre systems), contributed to obtain stiffer sandwich panels and to increase yacht lengths up to 45 m. Nevertheless carbon and epoxy laminates need more sophisticated production technologies based on the availability of large ovens to cure mouldings at high temperatures, not a cost effective production technique.

Classification societies had always been very careful in accepting sandwich for the whole hull shell because of the low resistance of the external thin skins to impacts. On the other hand shipyards are in favour of sandwich panels because it avoids secondary stiffeners, further simplifying the construction sequence, and because it allows smoother external surfaces without the shrinkage marks of internal frames. At present the use of sandwich plating, while utilised for the entire hull on sailing yachts, is only well accepted for deck and sides for motor yachts; for bottom structures single skin remains mandatory, especially for high speed vessels. In Figure 12 the main section of a planing motor yacht with a single skin bottom and sandwich side and deck is shown.

A further complex point for FRP yachts is the hull to deck joint; as reported by Pfund (1999) this is a critical aspect for boats over 30 feet for which hull girder loads become significant. He gives many suggestions for optimization with regard to strength and aesthetics, the latter not to be underevaluated at all.

Fuel storage on board FRP vessels is generally done in stainless steel tanks or in structural tanks integrated in the hull structure in way of a double bottom. The first solution is now well tested and reliable enough where safety and odour are regarded. Structural tanks, in principle, showed many problems especially with regards to fuel seepage. This has been solved by specific treatments such as gel-coating or some other impermeable barrier coat on the inside of the tank. Eikenberry (2009) presents common problems of installation and maintenance of different types of fuel tanks in aluminium, polyethylene, stainless steel and fibreglass. Collision and watertight bulkheads are FRP made with 'top-hat' stiffeners; dividing bulkheads are made of plywood sandwich with insulating panels as the core.

8 PRODUCTION METHODS

8.1 Wood

The traditional building methods of solid wood boats still relies heavily upon the ability and experience of shipyard craftsmen. However the production methods for wooden boats have been simplified by the introduction of plywood and lamellar wood, together with new epoxy based bonding systems which has significantly changed the hull structure lay-out. The lamellar multi layer shell and glued reinforcements avoid pin holes and joints, thus reducing the beam sections and increasing the frame distance. Lighter hull structures are therefore more achievable without sacrificing strength and stiffness. Many motor yachts are still built from wood therefore, typically up to lengths of 30 m and speeds around 20 to 25 $knots$. The same advantages of these laminated techniques are used in wooden yacht refits which are, at present, a consistent, profitable and prevalent industrial activity.

A new trend consists in building yachts by combining wood with composites: cedar strips are glued on a structural grid and covered by carbon reinforcements laminated with epoxy resin. Vacuum bagging is widely used for a better structural performance. Wood remains the primary structural material and it works as a mould for the external composite. Epoxy as an adhesive and a coating works much better than polyester resin with regards wood durability. Composite fabric is usually just a surfacing material that does not significantly contribute to structural strength. This construction method, suitable for medium size sailing and motor boats, has been described in detail by Fox (2001). Boote and Morozzo (2005) presented an experimental investigation to determine the resistance of multilayer beams of lamellar wood and carbon reinforcements for the construction of a racing yacht.

8.2 Steel and Aluminium

The construction procedures of a steel/aluminium yacht depend mainly on shipyard facilities and practice. As a general rule hull and superstructures are realised separately. Traditionally the hull was built on a launch slipway, starting from the keel and then adding all frames up to the deck and finally enveloping the whole with the hull shell. At completion the hull is launched and outfitted afloat. Nowadays, the hull is built in a shed allowing better working conditions, especially in colder climates, and then launched by means of trolleys and cranes. Similar procedures are used for aluminium vessels with the only difference that they are often built upside-down to take advantage of the deck as a flat support and reference surface. The lower weight facilitates the overturning operation. Nowadays, the standard procedure for larger yachts (over $40\,m$) consists in building the hull by blocks, as normally done for conventional ships. Block dimensions depend on their weight and on the lifting capacity of yard cranes; in case the weight is too high blocks are divided in height and, sometimes, in breadth by smaller modules. Modules and blocks are then assembled together in a slipway or in a basin and outfitted when the hull is completed. Preliminary block outfitting is not so common because it would require a very detailed and time consuming design procedure which is not advisable for yachts because of frequent design changes required by the owner. From the shipyard point of view this is the real difficulty in yacht construction management. Accordingly, the attraction of employing 'concurrent engineering' is being increasingly recognised as a boon to superyacht production.

An important issue is represented by the study of new welding techniques oriented to reduce distortion defects and consequent man hours spent in reworking. This problem, rather pervasive in steel constructions, is dramatic in large aluminium structures. Russell and Jones (1997) present a detailed analysis of laser welding advantages and disadvantages with regard to traditional Gas Metal Arc (GMA) and Tungsten Inert Gas (TIG) processes. The main advantages of laser welding are summarised in controlled and predictable component distortion, high joint completion rates, and easy integration with CAD/CAM and CIM operations. In the specific case of aluminium superyachts a reduced distortion means a high saving of filler and fairing work. On this same matter extruded aluminium panels with incorporated stiffener profiles offer many production advantages, especially for ease of deck construction where problems associated with weld distortions during stiffener joining can be mitigated.

8.3 Fibre Reinforced Plastics

Production methods for FRP motor yachts are very similar to those adopted for sailing yachts. The main difference is represented by the more complicated shapes of hull and superstructures which necessitate building the vessel from a higher number of components and, thus, a higher number of moulds. For smaller units, up to six to eight metres, two separate moulds for hull and deck/deckhouse are sufficient. The after body of the hull mould is generally a separate part to allow gangway stern shapes. By this solution, it is possible, at a relatively low cost, to make aesthetic changes to the after body and to obtain slightly longer vessels just by substituting the aft part of the mould. For bigger vessels, deck and superstructures are built by separate moulds as well, but the hull mould is preferably divided into two longitudinal shells to avoid lifting operations when extracting the hull. Then a number of minor components are laminated to complete the structure and the internal outfit.

The majority of FRP motor boats are built by a hand lay-up technique by which every reinforcement layer is laid into an open, female mould and manually wetted and rolled. As FRP material resistance is a compromise between the as high as possible glass content and complete glass wetting, the final material quality depends heavily on workers' experience and shipyard daily environmental conditions (dust, humidity and light conditions). The uncertainty of the material quality is further increased by the need to mix the resin with a catalyst to prime the hardening process: this action, generally carried out manually, heavily influences the material workability time and obliges workers to prepare small quantities of resin before lamination, thus wasting a lot of time. This inconvenience is overcome by the spray lay-up process by which resin and catalyst are sprayed at the same time and with correct proportions on reinforcements by a spray-gun fed by pneumatic air equipment. It is also possible, with a proper gun, to spray cut glass fibres together with resin to obtain an on site chopped strand mat. However, it is not easy to control the glass volume and the resulting thickness and again the material quality depends on worker skill. Nevertheless spray lay-up has the advantage of obtaining a constant, optimal resin/catalyst ratio, a longer workability time and yard efficiency in terms of production, but it still requires rolling operations to consolidate the laminate.

Apart from any other technical concerns, the most serious FRP problem is represented by the styrene fumes released in the working environment during the chemical process of the resin hardening in the mould, which have been proved to be toxic for human health. To overcome pollution new lay-up procedures in closed moulds have been developed and/or are under study. The first, well known solution is represented by the vacuum bag or vacuum consolidation procedure in which an airtight sheet, usually nylon, is used to cover the fibre stack in the mould. Reinforcements are wetted out as with hand lay-up. A set of plastic pipes properly placed in the mould and connected to one or more vacuum pumps allow atmospheric pressure to drive out the excess resin thus increasing glass percentage in the laminate with consequent better mechanical properties.

An improvement to this method, removing the disadvantages of the hand lay-up step and the difficulty in positioning and rolling wet reinforcements is represented by the 'vacuum infusion' process: the main difference with respect to vacuum bag is that reinforcements are placed in the mould when dry, without prior wet out; this allows a major accuracy in the positioning phase and it makes it possible to laminate the hull shell and stiffeners in one shot with significant time savings. The laminate stack is then covered by peel-plies, breather materials, vacuum distribution pipes and an airtight bag. Using vacuum pumps resin is first sucked into the dry laminate stack and then evacuated if in excess. The final result is a very compact product with a high glass percentage, good material quality and repeatability. This latter aspect becomes more and more crucial for large scale production which is currently only relevant for FRP boat construction. Infusion asks for a great care in the preparation of the mould, laminate stack and vacuum circuits: a small error in whatever phase can cause the loss of the whole material. From the environmental point of view by utilising the infusion process personnel have no contact at all with resin and no toxic fumes are dispersed into the working area during polymerization; on the other hand a large amount of

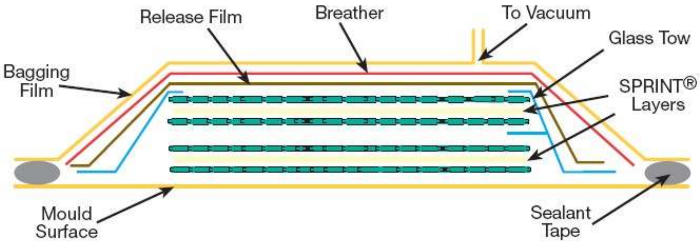


Figure 13: SPRINT system main components.

reject material (peel-plies, breather materials and plastic pipes) is produced for each moulding.

Vacuum bag and vacuum infusion are widely used to build sandwich panels as in one single operation the two skins can be bonded to the core. Moreover infusion is particularly suitable in the case of honeycomb cores, both Nomex and aluminium, because of the reduced bonding surface. It is then possible to produce large components entirely from sandwich construction, such as complete superstructures or decks, in one single process or to laminate partial areas in sandwich within a single skin hull or deck.

As specified in the previous ISSC 2009 V.8 report, vacuum infusion is a general term by which several similar procedures are addressed. Besides well known methods such as SCRIMP a new process has been patented as SPRINT (SP Resin Infusion Technology). SPRINT materials consist of a layer of fibre reinforcement either side of a pre-cast, pre-catalysed resin film with a very lightweight tack film on one face (Figure 13). The material therefore has the appearance of a dry reinforcement, which has resin concealed at its centre and it is produced by a process that differs from conventional prepreg so that the fibres in the reinforcements remain dry and not impregnated by the resin. SPRINT layers are laid up in the mould and vacuum bagged as for conventional prepreg. When the vacuum is applied, the air transport properties of the dry reinforcement enable air trapped in the fibre bundles and between layers to be easily removed, reducing the void content to extremely low values. When the temperature is then raised for the cure, the resin film softens and flows into the air-free reinforcement.

The benefits and drawbacks of the infusion process have been widely assessed in the ISSC 2009 V.8 report for sailing yachts and they remain for motor yachts. In short, whatever the type of process, vacuum infusion allows to reduce pollution in the work environment and to increase FRP mechanical properties, reaching glass percentage in the laminate close to an average of 60 % in weight (Boote *et al.*, 2006). At present the trend within shipyards is to apply more widely this methodology to bigger vessels and components and in many cases they build FRP motor yachts with lengths over $20\,m$ completely by the infusion technique, and other FRP components, such as decks and superstructures, for vessels up to $40\,m$.

The present trend to control production cost is represented by modular construction by which the vessel components are moulded separately and then assembled by bonding. From this perspective an accurate study of the minimum number of moulds and their optimization becomes very important for the industrialization process and cost reduction. The first applications of this method regards the realization of FRP counter-moulds in which the housing for furniture and fittings, and some furniture themselves, are included in the mould to speed up the interior furnishing; the tray was then glued to the hull structures, partially contributing to the hull strength. The second step is to build separately the hull shell and the reinforcement grid (also called 'spider structure') in two separate female moulds and then to glue them to each other; in this case the bonding procedure and the choice of the best suitable type of adhesive is more complex. Strand (2002) gives a comprehensive set of guidelines about modular construction, highlighting the problems coming from gluing fresh, uncured polyester laminates to cured ones. The solution is to use methacrylate adhesives which are proven to have strong adhesive capabilities coupled with acceptable elasticity.

9 OUTFITTING

Outfitting covers the whole fit out of a vessel from the interior to the exterior, engineering to aviation, bridge integration, luxury owner supplied items or toys and stores. As far as the conventional naval architect is concerned, weight estimates consider machinery separately from outfitting which includes the rest of the engineering systems and interior fit-out, the total lightship being made of hull structure, machinery and outfitting (a rational approach to weight estimation of fast crafts can be found in Daidola and Reyling, 1991). In this report however, outfit considers all installations that are not fixed parts of the ship hull. The issue of outfitting on structural requirements is crucial not only in terms of the fundamental systems that allow the operation of a vessel but in the case of luxury sailing yachts and superyachts in the features that provide the definition of luxury, including heli-decks, large open volumes, swimming pools and internal harbours and garages. However the complexity of outfitting varies between vessel types and the regulations underpinning vessel design and operation can vary between the very limited applied to a private yacht to those unrestricted charter vessels carrying more than 12 guests that therefore require cargo or passenger ship certification.

The role of CS in the outfitting process is considerable. While a class surveyor might inspect a hull moulding on two or maybe three occasions, the bulk of the surveyor's contact with the vessel will be in the pre-outfit and outfitting stages of the build. Particular attention in the early outfitting stages is paid to the structural complications referred to in the following sections, but clearly as outfitting progresses there is an increasing focus on systems installation. As stylists and designers become more innovative with materials and furnishings, including the increasing use of glass (Freivokh *et al.*, 2010), dependent on the classification of the superyacht, materials used in outfit must meet SOLAS approval. The relevant standards in all aspects of super yacht design and operation are reported in more detail in Chapter 3.

Outfitting also needs to be considerate upon the basic requirements of a charter crew required to operate the ship and the Maritime Labour Convention (MLC) ensures a minimum requirement for crew space which from an owner perspective can impinge on space available for guest and owner designated areas (The Superyacht, 2011).

9.1 Structural Challenges

A typical flow chart of the construction and outfitting process of a superyacht is shown in Figure 14. Outfitting is by far the longest and most complex process in superyacht production taking typically up to two thirds of the production time and up to 80 % of the superyacht production cost. The inclusion of large spaces, maximising internal volume and integrating systems to accommodate comfort, luxury and toys present significant structural challenges and issues relating to compliance vary from

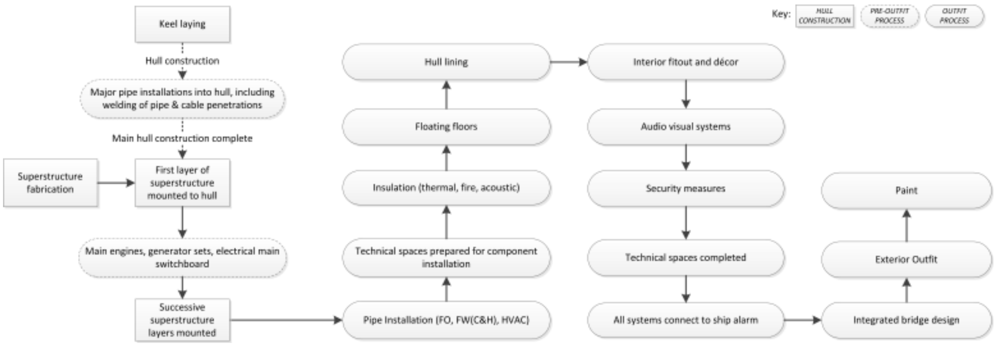


Figure 14: Generic hull construction and outfitting sequence for superyachts (Meijers, 2003)

the impact of the International Convention on Load Lines upon window sizes, to side shell openings, hybrid material connections (for example, aluminium superstructures explosively welded to steel hulls) and the stowage of toys to discontinuities in primary structure.

Optimising structural arrangements to ease outfitting imposes again the problem of transverse versus longitudinal framing structure. As vessels become larger, the relative increase in bending moment is influenced by the square of the length (and relatively modest increases in beam). Accordingly, as reported by Roy *et al.* (2008), the longitudinal framing appears to be more efficient because of deep and less frequently spaced transverse frames. With longitudinal framing, the length of pipe runs for outfit can increase but the weight savings in this alternative construction are penalised when the longitudinals' depth is increased to take cutouts required for HVAC systems to make transverse turns. 'Tween deck height is increased and longitudinal stiffening can lead to deep recesses in way of hull windows which often conflicts with client and interior design requirements. Hybrid framing systems whereby the side shells are transversely framed, allowing greater flexibility in vertical routing of services and decks longitudinally stiffened, appear to offer the best compromise for structural efficiency, maximised internal volume and accommodation for service runs. In addition longitudinal and hybrid framing best matches dimension increases. In Figure 15 two examples of the typical routing and 'tween deck space available for running service pipework and cabling is shown.

Figure 15: Typical 'tween deck depths for service runs (images courtesy of BMT Nigel Gee).

Superyacht systems are concealed and run in the most space economical manner possible. This can make access for installation (and still worse access for rework) extremely difficult, especially in the later build stages. As such the larger the amount of pre-outfit (particularly underfloor/behind carcass system installations) which can be carried out prior to the joining of hull and deck shells, the less access is a concern and the more man-hours are saved. As vessels get larger, the likelihood of penetrating primary structure for service runs increases. Meunier and Fogg (2009) presented research findings that show adding cut-outs within components such as structural bulkheads, will create an area of local stress concentration. With advances in 3D CAD/CAM software and availability, Meunier and Fogg reasoned that ensuring system penetrations are added in a non-critical areas for structurally efficient design is achievable at the earliest of design stages.

For craft constructed from composites penetrations in stiffening elements, such as deck beams, girders and frames, will be subject to both local reinforcement prior to penetrations being cut and local consolidation to ensure maximum structural continuity. Design criteria govern the maximum size, minimum spacing and overall geometry of penetrations to best preserve the global effectiveness of the stiffening. Finally the finishing details will be specified to maximise the strength and life of the penetration/stiffener interface.

Similarly, through hull penetrations must be carefully designed to maintain the local structural integrity of the hull. For composite vessels, the largest penetrations will be implanted into the hull mould to guarantee structural integrity and wherever a significant penetration is foreseen the local hull core will be chamfered out to reduce risk to the structure. Standardised fittings will then be used for monolithic laminate penetrations with specified fitting and finishing details and procedures. Where it is necessary to remove hull core in way of a penetration the core will be consolidated and made watertight in way of the cut-out to avoid water ingress as a result of damage in service.

A description of most effective outfit solutions on a motor yacht is presented by Lalangas and Yannoulis (1983): to reduce noise and vibration diffusion through the hull and superstructure spaces all the interior technical outfit is arranged with 'floating' floors and walls in such a way as to isolate as much as possible passenger areas. Insulating systems consists of paints, filler and panels applied to the internal cabin surfaces. In some cases to reduce the noise from hull wash, some planks are directly applied to the internal shell at the waterline. All these devices heavily influence the final displacement of the ship and a very refined structure scantling becomes mandatory.

9.2 Rework and Refit

Luxury superyacht builders report that rework can add thousands of man-hours to a project and may be a result of design or production errors at an earlier stage, unforeseen complications or client specified changes. The severity of the rework requirement clearly varies depending on the cause and timing, but in general terms, the earlier any required rework is carried out the fewer complications it will in turn result in.

For steel ships, a lot of the final challenge in production rests in fairing and painting the hulls to achieve the gloss finish required by the owner. Exterior rework to rectify weld distortion and fit is often avoided by using this fairing process and significant yard investments can be made in automated fairing compound applicators. Epoxy fairing compounds are stable as a coating but even with the low density bulking property of added glass microspheres, an average application of 20 *mm* for a 60 *m* yacht equates to an extra mass of 20 *tonnes* (approximately 2.5 % displacement mass).

Structural deformation (especially in aluminium) due to thermal loading is a big problem as well, both in terms of adhesion of fairing compound but more so in terms of cosmetic rippling, exaggerated by high gloss paints (dark or light). As the displacement mass is not so much of a concern to the superyacht designer (these vessels are rarely optimised in terms of power to weight) and if internal volume remains unaffected, then thicker plates provide less thermal distortion and little impact to cost (hull construction materials account for approximately 10 % of the overall yacht production cost). A problem exists however if structural mass for a stiffened plated section increases faster than increasing stiffness gains, then resonant frequency drops and vibration amplitudes from machinery noise, hull/water interaction and propeller excitation increase.

Owing to the huge number of existing vessels and their intrinsic value, the maintenance and refit market of yachts is a growing activity in yacht industry and it represents a source of steady flow, with the consistent by product of maintaining the value and good conditions of yachts, this aspect determinant for the top brands. Refit in particular represents a real new resource especially in recession periods, like the present one seems to be, and it is mainly oriented to big ships for which the value of the steel vessel is large enough to worth the business. This activity is carried out by conventional shipyards together with new constructions or, even more often, by specialised societies. Even if mainly oriented to interior work, often refit covers structural matters as well, especially in the case of older units. Most common interventions regard the modification of stern steel structure to achieve larger bath areas and/or to add a stern door to allow garage access, the addition of bulbous bow, the lengthening of aluminium superstructures, the addition of fixed or folding helicopter landing areas. Particular attention must be devoted in refit planning because all these works deeply influence ship weight and stability conditions and must be carried out in accordance to in force CS' rules. Refit project and work are often more difficult than for a new construction because it is impossible to know what to expect until the beginning of operations. In addition there are fewer degrees of freedom with respect to a new construction because it is not possible to change more than to a certain extent the aesthetic and functional nature of existing structures. Some important aspects of yacht refit are presented by The Superyacht Intelligence (2011) together with a long list of recent refit work carried out by most important refit shipyards.

9.3 Stability and Fire

Volume and expected mass of outfitting are determined early on in the design stage: Hulseman *et al.* (The Superyacht, 2010a) point out that it is important in the apportioning of available space and volume that the outfitters are consulted early so that the requirement for technological system space for, especially interior, outfit is recognised and properly accounted for. Vessel statics and operating dynamics are affected by the mass disposition: for a superyacht where capacity is important, the deadweight to displacement is low compared to, say, a cargo vessel which necessitates large deadweight carrying capability. In the latter design stages, superyacht stability can therefore be affected off initial design by changes in fitout to satisfy fickle customer requirements, although rarely is this shown to be significant. What is of more concern is the disposition of the deadweight, which whilst low (15 % -20 % of total weight) is constituted principally by consumable fuel load (60 – 80 %) which is deep in the vessel

(Roy, 2006). This results in light arrival conditions which are challenging with regard to static and dynamic stability criteria. It is the norm therefore that stabilising devices are fitted for comfort at anchor which puts more burden on structural requirements to accommodate these.

A large challenge is in the use of recreational fun tools, shortly called 'toys', whilst at anchor. Most superyachts are fitted with big tenders, jetskis, sports cars and so forth; helicopters are the present vogue. As an example the superyacht *Le Grand Bleu*, carries two tenders: a 62' Sunseeker and a 72' Baltic sailing yacht, and is equipped with two helipads. These changes in static stability must be accommodated by increased structural design and ballast arrangements but without compromise to internal volume. At present the concept of a dedicated vessel supporting the mother ship to carry toys is realised by the 'shadow yacht', the 'toy box of the sea' as defined by Sime *et al.* (2009); in their paper the ideal technical requirements for such a kind of vessel are described and a number of possible design solutions are presented.

Helicopters provide significant outfitting challenges in that the regulations governing the platform design and supporting infrastructure often clash with customer requirements and exterior styling. Articulating and folding platforms are the common solution but come with incumbent structural design impacts. A clear summary of design guidance for helidecks is presented by Strachan and Lagoumidou (2009).

MCA-LY2 requires all enclosed compartments in the hull and below the freeboard deck that are provided with access possible through openings in the hull (for example, inner harbours and garages) should be watertight doors fitted with alarms connected to the bridge. The actual openings in the hull should comply with SOLAS II-1/25-10 External Openings in Cargo Ships.

Swimming pools and SPA baths are considered to be 'recesses' (under LY2) and as such, as it is not practicable to drain them within the 3 minutes requirement, intact and damage stability must be considered accounting for the mass of water and free surface effect. Damage stability is assessed through ICLL or LY2. Vessels of $80\,m$ L_{OA} and above need a SOLAS one-compartment standard of subdivision. As vessels become increasingly longer, 2 compartment standard of subdivision becomes more normal which has positive benefits for exterior designers in the siting and provision of life-saving appliances. Refit or major alterations require new inclining experiment checks on lightship stability when either the displacement has increased by over 2 % or the L_{CG} has changed position by more than 1.1 % or the V_{CG} has changed by more than 0.25 % or at renewal survey every 5 years.

According to insurance claim records, the greatest danger to superyachts in terms of financial loss is fire in harbour (The Triton, 2006). Under the MCA-LY2 Regulations 14B.2 and 14B.2.14, all accommodation and service spaces except those not of high fire risk (sanitary spaces, etc) for a superyacht carrying up to 12 passengers must have an automatic sprinkler, fire detection and fire alarm system. This is not however mandatory for a superyacht that falls under the SOLAS Regulations if it carries less than 36 passengers. However if the automatic system is installed, then the fire integrity standard of the bulkheads and decks can be reduced according to SOLAS II-2/9.2.2.4. So at first sight it appears that there are structural and outfitting cost savings to be made by certifying the vessel as a passenger vessel and satisfying SOLAS rather than gaining certification through MCA-LY2. However, a big impact in the construction of a yacht under SOLAS rather than MCA-LY2 is in the restricted use of combustible materials and how the fire doors are constructed (Fanciulli and Moretti, 2009). Fire integrity of divisions (under SOLAS or LY2) needs to be maintained at openings and penetrations which can be lead to practical complexities following Gurit's findings (Meunier and Fogg, 2009) on increased primary structure penetrations with the increasingly larger vessels being built. One example impacted by luxury outfit requirements comes in the shape of saunas and steam rooms where an 'A' class boundary is required.

9.4 Security

The increasing size of the superyacht fleet, their inherent unit value per ton and the value of the guests belongings and the yacht's freedom to roam make them attractive targets for criminal and terrorist activity. The subject of security on ships and yachts is regulated by the International Ship and Port Facility Security Code (ISPS, IMO 2002) which is a comprehensive set of measures to enhance the security of ships and port facilities. The ISPS Code was adopted by a Conference of Contracting Governments to the Solas 1974, convened in London (December 2002). The Code aims to establish an international framework for co-operation between Contracting Governments, Government agencies, local administrations and the shipping and port industries to detect security threats and take preventive measures against security incidents affecting ships or port facilities used in international trade and to establish relevant roles and responsibilities at the national and international level.

From the operative point of view some measures can be adopted to enhance the security of yacht when at rest and sailing. Figure 16 shows some of the common security measures being incorporated into superyachts:

- thermal imaging cameras for day and night vision mounted in high and protected positions;
- underwater cameras mounted at fore and aft to verify approaching divers;
- underwater lighting to control the yacht surroundings both below and above water;
- gangway entry video-phone to control entrance when in port;
- radar based detection systems to individuate approaching craft;
- long range acoustic guns, high pressure water guns, pepper guns;
- 'shadow yacht' carrying security guards to support the mother ship.

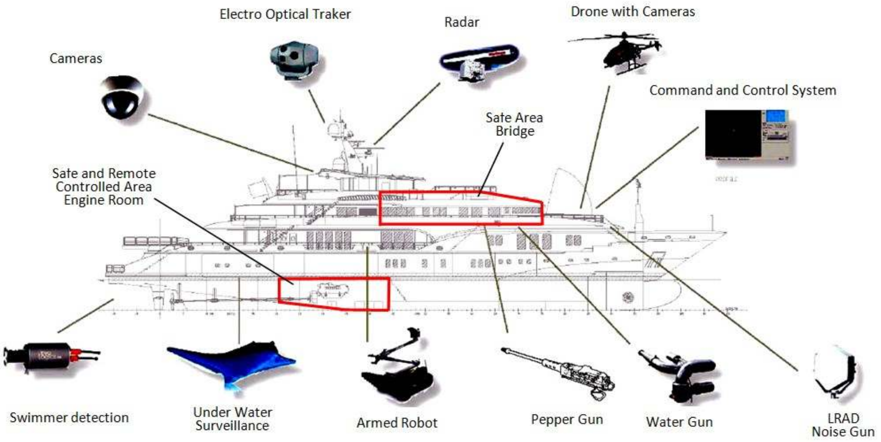


Figure 16: Security devices available for superyachts (by courtesy of Nobiskrug Shipyards)

Two issues regarding structural capability therefore exist. Firstly, the introduction of security measures requires integration into the yacht's electronic systems, placing more burden on the limited 'tween deck space and structural penetrations for cable runs. Secondly, extreme protection is provided by the hardening of safe areas of the yacht, typically the bridge, to mitigate high velocity rifle rounds and blasts. The engine room must be locked remotely and all essential cable trays protected in order that the bridge has full control over the yacht (The Superyacht, 2010). All the considered solutions can be carried out on existing yachts but could be more efficient if integrated in the design phase and realised during the vessel construction. The integration of a system always means higher efficacy and lower costs with respect to a retrofit intervention.

10 SAILING YACHTS

The report of the V.8 ISSC Committee on Sailing Yacht Design (2009) had an extensive discussion on materials selection, fabrication techniques, and design procedures for sailing yacht hull, rig and appendage structures. This chapter is an update of that report, citing the recent work that has been published and some other papers not quoted in the 2009 report.

10.1 Hull Design and Structures

During the past 3 years, the majority of the research into sailing yacht problems seems to be in the application of advanced numerical techniques to sailing yacht design. In particular, computational fluid dynamics (CFD) and finite element analysis (FEA) are being used to more accurately predict the loads on a yacht hull and the responses of the hull structure to those loads. Many CFD applications investigating the determination of loads for structural design are available in literature. Similarly the use of finite element analysis (FEA) in analyzing sailing yacht structures is increasing with the improvements in software and hardware. Fornaro (2011) discusses in detail the entire process of using FEA to analyze the behaviour of composite yacht structures from pre-processing to post-processing. The pre-processing includes meshing, ply properties, laminate definitions, element orientation, global ply tracking and load case development. Post-processing topics include principal stresses, failure indices and strength ratios. Most FEA analyses for composites use linear static solution methods that imply an assessment of strength based on the first-ply failure. Nonlinear solutions allow progressive ply failure analysis (PPFA) by sequential degradation of stiffness for the first and subsequent plies failing until complete failure of the laminate has occurred. The results of PPFA are a better understanding of the nature of failure in a given area and the amount of reserve strength following initial ply failure.

The optimization of composites is much more difficult than for isotropic materials because of the increase in the number of possible design variables such as number of plies, ply thickness, fibre orientation, core material and thickness, etc. Anderson (2008) provides an overview of common optimization routines and briefly discusses their good and bad attributes. Achieving a robust, optimum solution for a composite structure requires not only a good understanding of FEA and composite structures, but also the optimization process being used and how composite structures are manufactured; attempting an optimization without this knowledge will likely result in problems.

Most composite yacht hull and deck structures use some type of cored construction to save weight and cost. High pressure slamming loads can cause significant damage to cored hulls. Two recent papers discuss the design of cored composite structures for dynamic slamming loads: Battley *et al.* (2008) experimentally characterized the hydroelastic responses of composite hull panels. Panels were tested at a deadrise angle of 10° and a range of impact velocities. Results showed that stiffness has a significant effect on the responses of the panel to a slamming-type load. Flexible panels had reductions in the peak pressure at the centre of the panel and increases near the chine edge of the panel, possibly due to the panel deflections that caused a reduction in the local deadrise angle. Islin and Lake (2008) studied low cycle-high elongation fatigue performance of foam core materials. Four cores were tested including PVC foam, two cross-linked PVC foams and a styrene acrylonitrile (SAN) foam. When subjected to slamming loads, significant differences were found between the cores. The three PVC cores retained or in some cases increased the area under their post-fatigue residual strength load-deflection curve. On the other hand, the SAN core showed a significant reduction in shear energy absorption and elongation after fatigue loading, indicating that this material may not be suitable for areas which would be subject to recurring slamming events.

A wide analysis of most relevant aspects of large sailing yachts made in composite materials is contained in the paper by Meunier and Fogg (2009) where they take into particular consideration hull girder strength, fore and aft structural requirements and the influence on hull structure weight. Comparative analysis of single skin and sandwich solutions is carried out. The paper closes with some considerations about structural versus aesthetics and comfort requirements. The structural behaviour of cruise and racing yachts from the comfort point of view is illustrated by Payne and Siohan (2008) who highlight the common conflicts that arise when integrating structures with the interior requirements. Battley (2011) in his paper considers specifically structural characteristics relative to slamming loads on sailing yachts.

10.2 Mast and Rigging

There have been relatively few publications on developments in mast and rigging analysis and design compared to the sails which they support. Rizzo and Boote (2010) present the structural design of mast and rigging from a practical viewpoint, highlighting main idealization concepts of structural behaviour. After a detailed illustration of the analytical available procedures and applicable rules, they discuss more complex scantling procedures, with particular attention to nonlinear finite element analyses, able to take into account nonlinear large deformations and slacking behaviour of rigging and sails. Some applications on a typical modern sailing yacht rigging are carried out as well. The design of mast and rigging is made more difficult by the uncertainty of sail loads transmitted to the rigging. The measurement of these loads in real scale is becoming a necessity especially for large sailing yachts. A measurement system to be fitted on Perini Navi sailing yachts has been developed recently by the shipyard at the Department of Naval Architecture of the University of Genova (Rizzo *et al.*, 2009).

Chapin *et al.* (2011) have considered fluid structure interaction in the design of yacht sails and rig using a viscous flow solver and a nonlinear finite element code which are loosely coupled. By iteration and using a genetic algorithm, optimum sail shapes can be investigated, and the loads transmitted to the mast and rigging estimated. Augier *et al.* (2011) have carried out a full-scale study in a J80 yacht, making simultaneous measurements of navigational parameters, yacht motions, sail shape and loads in the standing and running rigging in unsteady sailing conditions. These measurement results were compared to a fluid-structure interaction numerical model and a good comparison was found.

The advantages of using streamlined carbon fiber rigging as opposed to conventional round rod rigging are discussed by Martin *et al.* (2011). By using a VPP for an IMS 40 yacht, they found that victories of 3 to 10 boat lengths could be obtained for both windward/leeward and Olympic courses.

10.3 Appendage Design and Construction

Similar to the advances in hull design and construction, most of the published work in the last few years has been on the application of advanced numerical methods. However, the paper by Keuning and Verwerft (2009) gives a new method to compute the lift forces on a keel and rudder of a sailing yacht based on the extensive data obtained from testing the Delft Systematic Series of yacht hulls. The final results are formulas for the lift on the keel and rudder that take into account the interference effects of the yacht hull, the aspect ratio, the sweep back and the downwash effects of the keel on the rudder. Orych *et al.* (2008) use potential flow methods coupled with a boundary layer code in order to study the effects on keel winglets on the lift and drag. Hutchins (2008) used a RANS code in conjunction with a VPP to determine the effects of candidate bulb shapes on the overall yacht performance. Canting keels are increasingly popular for high performance racing yachts. However, the canting keel imposes unique loading situations on the yacht structure. The structure needs to be strong enough to withstand the very high loads generated by slamming and grounding and yet light enough to not counteract the advantages of the moving ballast in the first place. Campbell *et al.* (2006) discuss the development of the Volvo Open 70 Rules regarding structural requirements for canting keels with particular regard to the safety considerations. Cowan and McEwen (2006) discuss the relative merits of various structural configurations and the use of FEA to analyze the keel configurations. Other practical aspects of canting keel are presented in Tier *et al.* (2006).

11 CONCLUSIONS

Superyachts, both motor and sailing, are very special marine products which lie outside the common criteria for the design and construction of conventional ships. Even if, in many cases, performance requirements continue to be the driving key of the project, the most binding aspects concern more the interior and external design rather than structural issues. Thus the stylist becomes the project leader and the engineer has to manage to fit the boat around the stylized design. This sometimes gives lots of problems/restrictions on the structural engineering side as well, but also commits the engineer to develop very clever and, often, innovative structural engineering solutions.

Furthermore, given the high intrinsic value of superyachts, every owner wants something special, new, and better than what the other owners have. This again makes yachts an ideal platform for research and development of engineering techniques and technologies to reach maximum passenger comfort, highest luxury levels and structural improvement as well. Regardless, the reliability and safety of the vessel is expected and this is reflected in the design and scantling of hull structures. From this point of view, whilst small and medium size yachts have their own rules and design procedures from Classification Societies, whereas larger yachts fall within conventional ships or HSC Regulations, the following trends and research expectations are common:

- light structures to reduce ship weight, construction cost and fuel consumption;
- structure optimization to allow for larger internal volumes;
- reduction of vibration and noise;
- material developments with particular emphasis on new composite 'eco' products and related emerging technologies.

As for conventional ships, many problem areas are still unexplored or, at least, unsolved. As far as future research on superyachts is concerned, the following aspects deserve for further investigation:

- direct application of structural optimisation techniques during the earliest design phases;
- parametric procedures for hull structural scantlings which can rapidly accommodate the changes requested by the owner, with low cost and with the possibility to evaluate the consequences of different alternatives;
- increase in the size of FRP vessels in order for superyachts to benefit from relatively low vibration behaviour and hull maintenance;
- integrated use of CFD and FEM techniques to achieve and apply realistic loads on innovative structures.

Finally, special consideration must be directed to outfitting: while building the hull structure takes one year, at least two or more years are required for completing the vessel. Particular attention should be devoted to improve outfitting design and production methods by use of automation techniques, such as fairing and painting, or modular construction for piping and furnishing. Given that safety and reliability remain imperative, it's the 'toys' and the systems that the owner is more interested in, and although this in itself is not strictly a structural issue, it does have serious consequences in terms of structures.

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