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COMMITTEE V.8
SAILING YACHT DESIGN

Mandate

Concern for the structural design of sailing yachts and other craft. Consideration shall be given to the materials selection, fabrication techniques and design procedures for yacht hull, rig and appendage structures. The role of standards, safety and reliability in the design and production processes should be addressed. Attention should be given to fluid-structure interaction effects on hulls, rigs and appendages and their influence on structural design.

Members

Chairman : A. Shenoi
R. Beck
D. Boote
P. Davies
A. Hage
D. Hudson
K. Kageyama
J. A. Keuning
P. Miller
L. Sutherland

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1. INTRODUCTION

The history of yachts goes back a long way. The first appearances were in the 1600's when wealthy Dutch merchants built and sailed small and relatively fast boats called "jacht" especially for pleasure. The real building and use of yachts sprung into life at the end of the 1800's. In the context of the present report we will restrict our self to the period starting a little before the Second World War up to the present day.

Originally "jachts" were built in wood and in construction quite similar to what was customary in the normal shipbuilding of that time. The hull was single (massive) planking connected to closely spaced wooden frames. The frames were connected to wooden floors and those to the bottom planking. In the early days many yachts still had flat or slightly curved bottoms. At the upper side the frames were connected to the deck beams on which the deck planking was laid. Longitudinal stringers were mostly absent.

Later when yachts got keels the construction changed. The sections became rather more V shaped asking for different construction techniques. The stem beam, the keel beam and the stern beam were introduced, which functioned also as longitudinal stiffeners, to which the frames were connected, which in turn were connected by the floors. The difficulties and weaknesses in the available connecting techniques of that time however posed a serious limit on the achievable overall strength and in more in particular the overall rigidity of the yacht hull structure. All wooden construction was only to return in yacht building after the 1970's, when new and serious bonding techniques became available, such as the epoxy resins, together with new wood laminating techniques.

So in the 1930's the new "composite" construction technique came into force, in which the keel, stem, stern, frames, beams and floors were all constructed in steel (and bolted or riveted, later welded together) to which the still wooden hull and deck planking was connected. This was a big improvement but still rather heavy.

Still later the completely steel hull came into play in which now in the composite d construction also the wooden hull planking and later also the wooden deck planking was replaced by steel and all were riveted or welded together. This yields a sound and stiff construction for the hull.

This construction technique, using either steel or aluminium, lasts till today and is mostly favored for the bigger yachts or for yachts with high demands on resistance against external local loads, such as yachts designed for use on long ocean voyages or in the arctic regions.

After the 1950's the new construction material "glass reinforced polyester" saw the light in yacht building. First it enabled series production of yachts bringing the ownership to a wider public. Then the introduction of the more general "fibre reinforced resin" materials and construction techniques brought a complete revolution in the construction of yachts. First the material was used in constructions quite similar to the traditional construction in wood: i.e. with frames, girders, floors, beams and the lot. Common practice was also the use of solid and rather thick laminates to overcome the lack of stiffness of the new material. It took some time for the industry to realize the full potential of the new material and to grow to more adapted and mature construction techniques. Monolith hull and deck constructions were introduced with integrated stiffeners. To be followed shortly by the very light weight and very stiff sandwich construction technique using a low density foam or wood as core material and very thin inner and outer laminates only. For 15 years now also the use of very high quality fibres with astonishing mechanical properties, such as aramid and in particular carbon fibre, has revolutionized the construction of high performance yachts again and enormous gains in overall weight, strength and stiffness have been achieved.

These are all fields in which the yacht building industry became the front runner, and many developments originated from the yacht building industry experiments. The yacht building industry also became the one which was confronted with the associated problems and challenges first.

A similar development can be noted in the evolution of the rig. In the early day's wood as construction material was the norm. Dimensions and the layout of the yacht rig were restricted by the available lengths of wood till adequate connecting techniques (gluing) became available. Still the wooden mast was rather voluminous and therefore heavy. All of this had a serious negative effect on the performance of a sailing boat.

In the 1930's aluminium alloys became available as construction material for masts became available and this introduced the possibilities for much lighter and slender masts. Also the stiffness of the mast could be improved as well as the quantity and the layout of the rigging.

From the 1980's onwards the composite mast was introduced. Originally they were constructed in the more traditional material glass fibre reinforced polyesters such as in the so called Freedom rig. For over 25 years now carbon fibre and epoxy resin have been introduced for mast construction. In combination with very high tech production techniques this has enabled a revolution in mast weight, stiffness and performance Also masts and rigs have been produced like the Dyna Rig, that would not have been possible in any other material.

This is the first time that this subject of yacht design has been broached in an ISSC forum. Consequently, a slightly wider search of literature and background references has been made with regard to hull structure, masts and rigging and appendages and keels. It has also been necessary in some areas to elaborate on the topics and themes in a fundamental manner. This examination of literature has been backed up with consultations with leading industrial houses in design and construction of yachts and rigging.

2. THE QUESTIONNAIRE

Given that this topic of sailing yacht design is one of increasing industrial interest, recognising that there was a high likelihood of literature in the open domain in the concerned disciplines being sparse and noting that considerable empirical wisdom resides amongst industrialists, it was decided to consult industrial colleagues through a questionnaire. The principal purpose of the questionnaire was to record factual information about a range of issues such the types of boats being built, the materials and methods of construction, design codes used and the product/production models deployed for construction.

The information received about the current status vis-à-vis industrial practice is recorded in Tables 1 and 2 (see end of Report).

Table 1 indicates that, amongst the businesses that responded, most were concerned with racing/cruising/mega yachts and used a wide variety of polymer composite materials, metals and wood. Caution though needs to be exercised in deciphering the details. The questions posed were general in nature; they were not specific in terms of, for instance, the functionality and whether the materials were used in a structural, aesthetic or secondary purpose. For example, wood was mentioned by several industrialists as a material used by them. It is well known though that there are very few boats or even structural members in boats that are constructed of wood. Equally, though many industrialists mentioned that they used or specified polyester, vinyl ester, epoxy and phenolic resins, it is likely that most used just one or two varieties in large quantities, with the other resin types being used for specialist applications.

Table 2 also is abbreviated and needs to be interpreted with care. For instance, the codes listed in the table are the ones we know for certain refer to materials and structural standards. The industrialists also\listed 'design codes' from the American Boat and Yacht Council (ABYC), ICLL, IMO, Marine and Coastguard Agency of the UK government and USCG rules. Some, such as IMO regulations, are simply not applicable to small craft and may have been listed as being among the regulations used by that company, presumably for larger vessels. Others, such as ABYC, whilst having some structural relevance for minor items, may have been listed for electrical and engineering installation purposes. As in the previous table, many industrialists listed a wide variety of composites processing and production techniques amongst the approaches they used. Again, this may be because many of the organisations who responded to the questionnaire were designers and consultants rather than builders of series production yachts. This may also explain for some terminological issues. For instance, some industrialists referred to the use of resin transfer moulding (RTM) for building yachts or their structures. This is difficult to reconcile because, firstly, RTM is most effective and efficient for large production runs, which are not found in mega and racing yacht fields, and, secondly, in the context of series production, the expense and down time is likely to make it impractical for economic production.

Notwithstanding these relatively minor comments, Tables 1 and 2 provide a collated set of information about the current state of art in industrial practice.

3. HULLS

3.1 Loadings and Methods of Assessment

Determining the design loads for the hull is a difficult problem. There are many different loads that must be properly accounted for. Similar to ships, the hull is subject to hydrostatic pressure along with dynamic loads due to waves, slamming, grounding and collisions. Unlike ships, sailing yacht hulls are also subject to sailing loads due to the sails and rigging. The mast(s) is in compression and the stays and shrouds are in tension, leading to large longitudinal and transverse bending moments on the hull. Complicating the loading and stress distribution is the fact that sailing yachts can have up to 60% of their weight concentrated at the keel attachment point which is often near the base of the mast; for IACC boats the ballast ratio is over 80%. In addition the loading is often asymmetrical due to the heel of the yacht and the sails being to one side. The loads experienced by a sailing yacht are illustrated in Figure 1.

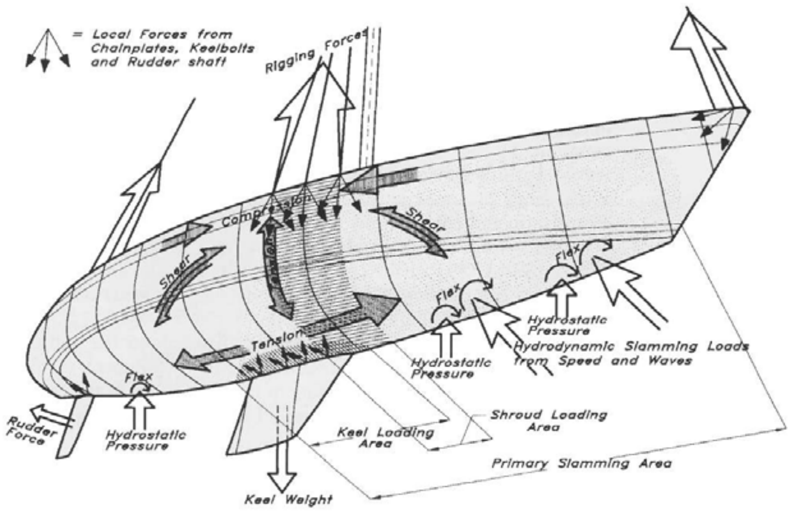


Figure 1: Forces on a sailing yacht (Larsson, 2007).

Yachts can also be subject to large loads while being put into and removed from the water. Boats up to approximately 10m in length are often put on trailers where the hull is supported by a few rollers as point loads. Larger yachts are put into and removed from the water using travel-lifts and slings that normally support the hull in only two places. The loads from trailers (if appropriate) and travel-lift slings depend only on the weight of the hull and are easily predicted. They must be checked during the design stage and for some yachts could be the critical design load for the hull scantlings.

Sailing yachts are also subjected to impact loadings arising from a large range of possible impact events, from collisions with other craft or floating debris and grounding to everyday docking bumps and objects dropped onto decks or inside the hull. Impact damage may of course be dangerous because a breach may lead immediately to the loss of the vessel, but also because less severe damage may significantly weaken the vessel's structure. Further, damage may grow with cyclic loadings leading to a catastrophic failure under normal loading.

The hydrostatic loads in calm water are easily determined, but typically they are not the critical design loads. The real challenge is in predicting the hydrodynamic and rigging loads on the hull due to sailing, particularly in extreme conditions. Rigging loads are discussed in Section 4 and hence will not be further mentioned in this section. Design hydrodynamic loads will be the main focus of this section.

There are a limited number of studies into predicting analytically the loads on sailing yacht hulls. Recently, various nonlinear methods have been developed to predict the design loads for ships operating in a seaway. For example, the ISSC committee report (2000) on "Extreme Hull Girder Loading" reports on nonlinear time-domain codes that can determine the nonlinear loading on a ship. An overview of nonlinear methods for a ship at forward speed is given by Beck and Reed (2001). Alford and Troesch (2008) present a method to create a wave amplitude time history with a specified extreme wave height that can be used in a nonlinear, time-domain ship motions code.

A great deal of research has also gone into predicting pressure loading due to water impact that may have direct application to the analytic prediction of loading on yacht hulls. Korobkin (2004) gives an overview of various water impact models that have been developed. Most water impact theories are for a constant velocity, vertical entry. Sailing yachts are often heeled and the theories must be modified for asymmetric sections. Judge *et al*. (2003) present results for wedges entering the water at oblique angles. Since water impact happens on an extremely short time scale and the pressure peak is localised near the spray root line and travels very fast across a given panel, the elastic response of the local hull structure becomes important (see for example Faltinsen, 2000). Ideally, the plating and stiffeners in areas susceptible to slamming would be designed using hydroelastic analysis that takes into account both the hydrodynamics and structural dynamics of the problem.

An alternative approach to predicting the dynamic pressure loadings due to water impact and attempting to apply these directly to a hull structural model is to use the concept of an equivalent uniform static (or effective) pressure. These correspond to the pressures which, if applied to a particular structural component in a static manner, will result in the same maximum deformation and maximum stress as produced by the actual dynamic loading (Allen and Jones, 1978). Such an approach is also common for high speed motor vessels. Obtaining such an equivalent uniform static pressure using experimental data for an array of pressure transducers over a model, or full-scale, hull is difficult due to the non-uniform distribution of pressure over the hull following a slam and the very short time period associated with the event.

Realistically, many designs are undertaken using static analysis with such a slamming design pressure and reduction factors to account for location, panel size, structural dynamics and type of boat. The slamming design pressure typically depends on the size and speed of the yacht. Joubert (1982) analysed 7 actual yacht failures or large plastic deformations that occurred when beating to windward in gale force winds. Using a knowledge of the hull structure, Joubert was able to hind cast the slamming loads that would be necessary to cause the damage. Using four different analysis techniques (linear theory, membrane stresses, plastic deformation analysis, and plastic limit theory with large deformations) he found widely differing pressure predictions. Joubert's final conclusion was that although the data is sparse the bottom panel loads on 40 foot length yachts beating in a gale may involve slamming pressures as great as 80 psi.

Attempts have been made to use model scale experimental data to obtain the average load on a representative panel area of the hull bottom involved in a slam impact. Such an average load may be obtained through the use of 'slam patches'. These are panels, representative in area of a full-scale hull panel, of high stiffness cut out of a hull model and attached to a load cell via a rigid strut. The load cell then records the average external pressure load acting on the panel. Such a technique, first used for motor vessels (Purcell *et al*, 1988), was applied to an Open 60' yacht by Manganelli *et al* (2003). Through extensive experimentation they found equivalent slamming design pressures for the yacht travelling in waves in both upright and heeled conditions. An analytical method developed for comparison to the experimental data including hydroelastic structural effects indicates good agreement. No comparisons to pressures predicted (or used) by Classification Society rules are presented.

Other research specifically directed towards the prediction of sailing yacht loads may be found in Boote *et al*. (1985) who examined a finite element model and a classical longitudinal strength approach to an aluminium 12m yacht in calm water. They also discuss full scale trials, although little data is presented. Ward (1985) analysed the dynamic stresses in a beam due to a slamming like pressure peak travelling across the beam. This simplified problem has direct application to the impact forces on the bow sections of a yacht sailing to windward. Ward finds similar tends as used in the ABS empirical impact reduction factors.

An extensive hydroelastic analysis of a WOR 60 yacht was conducted by Louarn and Temarel (1999). Using a combination of finite element analysis for the structure and linear potential flow theory for the hydrodynamic loads, they found that the largest stresses were in the vicinity of the hull to keel joint area. The effects of heel and rigging loads were included in the analysis.

3.2 Structural Responses and Methods

Loading results in structural deformation and material stress and for marine applications the most critical can be grouped as global bending or torsion, panel flexure and joints. As discussed in the section on hull material selection the most common materials used today are composites and the method to analyse the stresses in a composite structures are critical to the accuracy of failure prediction. The reason for these becoming the most critical relate to the ability to tailor laminate performance and the inherent weakness of the matrix as an adhesive. Numerous analysis techniques, ranging from simple empirical "rules-of-thumb", to classification society rules, and to advanced numerical modelling through finite element analysis (FEA) are used. The selection of the appropriate method largely depends on the design complexity and owner's requirements and budget. With the increasing power of the personal computer and the wider availability of sophisticated analysis software, more small craft designers are acquiring and applying advanced methods.

Traditional Classification Society rules and codes for sailing craft, reflecting common practice, used isotropic beam and plate equations combined with empirical factors to resolve the loads in to the structure (Curry, 1989). Analysis was strictly linear and material ‘knock down’ factors based on fatigue and other uncertainties were combined to produce minimum required scantlings (see Figure 2). Due to the small size of most sailing yachts the primary analysis focused on plate and framing analysis in response to hydrostatic pressure loading. As this analysis usually resulted in relatively large scantlings, global hull girder bending due to waves was largely ignored. Rig loads, particularly forestay and backstay loading, combined with the keel loading could produce sufficient global hull girder bending to cause deck buckling and was included in shallow depth racing yachts. With regards to America’s Cup Class yachts, which have a narrow hull, heavy ballast and tall sail plan, the bending moment is large and the load in the midship region may be over 100kNm. The bending moment is then the dominant load in determining suitable hull scantlings (Figure 3). Composite materials were treated as isotropic with a single modulus and the strength determined from testing (Gibbs and Cox, 1960).

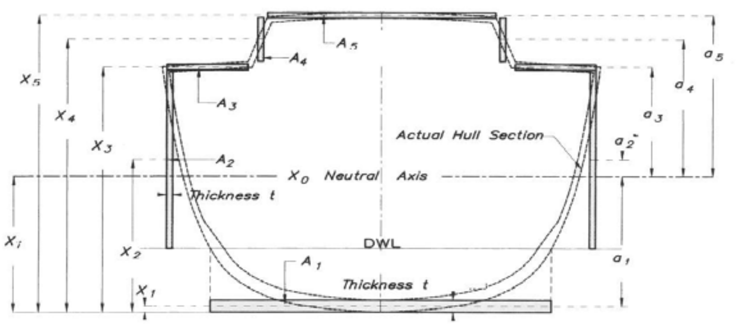


Figure 2: Example of simplified section of hull girder section (Larsson and Eliasson, 2007).

Figure 3: Bending moment diagram for an America`s Cup Class yacht (Larsson, 2007).

In recent decades the trend toward lighter hull skins of composites required ply stresses to be correctly analysed. One approach is a modification of the isotropic beam and plate method where laminated plate theory (also called classical lamination theory) is used to resolve the multiple ply stack into a blended isotropic material of equivalent stiffness. This is then used in the isotropic plate theory to determine a maximum plate strain. The strain is then applied back through the laminated plate theory to predict ply stress. This approach works well with balanced, symmetric laminates of predominantly woven and mat materials and was an easy fit to the empirical scantling rules.

When the laminates include significant unidirectional laminates, or are unbalanced or asymmetric the blended plate theory does not produce acceptable results as the isotropic plate analysis cannot predict an accurate strain field. In this case loads have to be resolved in to forces and moments that may be directly analysed using laminated plate theory. Due to the complexity involved in resolving these forces and moments two approaches may commonly be followed. In the first case a “worst case” loading location is found and the laminate developed. Typically this would be in the slamming area on the centreline. This laminate would then be applied to the entire hull, or would be tapered slightly above the normal heeled waterline. Localised reinforcements would be applied for point loads such as chainplates and the mast and keel foundations. The second approach uses classical orthotropic plate theory as traditionally applied to large vessel plate and beam calculations.

To maximise laminate tailoring, however, a resolution of all the loading is required. The current method practiced is through the use of global hull finite element analysis (FEA). Predominantly used only in the domain of high performance vessels, its use has been documented from dinghies (Riber, 1993) to small (Miller, 2000) and large cruising (Miller, 2003) and racing yachts (Hamilton and Patterson, 1992). An example for an America’s Cup Class yacht is shown in Figure 4. Typical FEA of hull structures uses linear analysis, however in places where large deformations or non-Hookean material properties are possible, then geometric or material non-linear analysis must be used. Typical examples include snap-through buckling and thick core materials, respectively. A finite element analysis with shell elements, which is currently the most commonly used, does not work well for estimating the core strength of sandwich panels accurately. For dynamic response to events such as slamming especially, confirmation through physical testing is necessary. In the DNV rules, the test method is provided in order to predict the slamming impact speed of sandwich panels (Lake, Eaglen, Janes. and Battley, 2007).

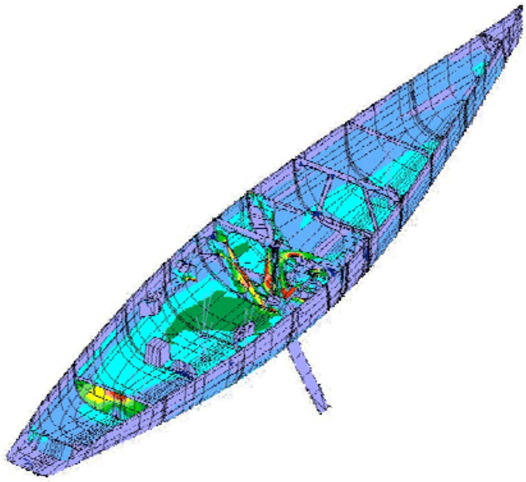


Figure 4: Example of finite element analysis for an America's Cup Class yacht (Uzawa, 2001).

Composites are susceptible to out of plane damage due to impact loadings (Abrate, 1998) and such damage may be especially dangerous since it will probably be mostly internal delamination and remain undetected. Impact response is dependent on many impact and material parameters (Sutherland and Guedes Soares, 2003), and the impact behaviour of GRP is complex (internal delamination, fibre failure, perforation, membrane, bending & shear effects, indentation etc) (Sutherland and Guedes Soares, 2006, 2007) it is very difficult to define exactly what we mean by impact behaviour or even which type of impact behaviour is 'good'. Firstly, which impact event should we consider? The response will vary greatly depending on which impact event we are considering. For example, one material/structural arrangement could well excel for a slow, head-on collision with a dock side, but be very fragile to a fast, oblique impact with a small, sharp floating object. The response to repeated water impact may well be a completely different case again, and specific tests have been developed to simulate this (Choqueuse *et al*. 1999, Downs-Honey *et al* 2006). Secondly, should the material/structural arrangement absorb the impact energy, or be resistant to penetration, or be resistant to impact damage? These are often mutually exclusive. For example, a Kevlar bullet-proof material (which is designed to absorb the impact energy of a projectile by suffering terminal damage in a one-time catastrophic event) would very quickly become structurally useless if used to construct a yacht deck (which is constantly subjected to minor impacts such as heavy foot-falls and equipment drops). Figure 5 shows how impact loads can be included in a multi-hull FE model (Casari *et al* 2008).

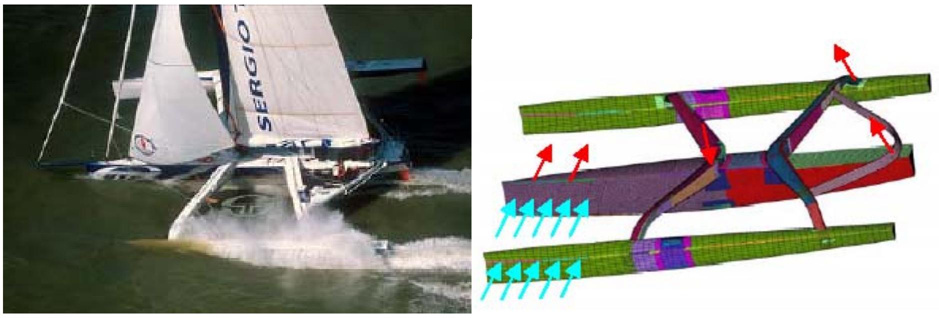


Figure 5: FE modelling of impact

3.3 Rules and Design Standards

The traditional approach to designing a yacht hull structure is to use a classification society's rules such as Lloyd's Register (LR) or the American Bureau of Shipping (ABS). The International Standards Organisation (ISO) is developing a new standard (12215) that is mandatory for all boats less than 24m in length which will be sold in the European Union (mandated through CE directives). The importance of the European market to most yacht builders means that the ISO standards are becoming a universal standard. These are a complete set of rules inherent to motor and sailing yachts. The ISO standards philosophy, similar to Classification Societies semi-empirical rules, consists in differentiating motor from sailing yachts in the design loads calculation and structures inherent to the vessels. Larsson and Eliasson (2007) discuss the ISO rules so far as they have been developed. In essence, the scantling rules define different pressure loads to be applied to various parts of the structure such as the bottom, topsides, deck, cabin sides, etc. The different parts of the hull are further subdivided as necessary. For instance, the highest pressure loads are associated with the forebody bottom where slamming damage is most likely to occur. It should be noted that the design pressures should only be used with the scantling rules for which they were developed because the two are a compatible pair. Typically, a base pressure (or head) is defined that depends on the size of the yacht. The base pressure is then modified by correction factors to arrive at the design pressure for a given plating location. The correction factors depend on such factors as location of the panel, whether or not the panel will be subject to slamming pressures, and the size and aspect ratio of the panel. The design pressures are then put into formulae including the design stresses to arrive at the required minimum panel thicknesses. Once the plating thickness are determined, the stiffener sizes and bulkhead sizes can be determined based on the associated panel loadings and stiffener spacings. The scantling determination of structural components is performed with a unique procedure for motor and sailing yachts, independently from the construction material. The rules also specify design loads for the determination of keel and rudder scantlings as well as hatches, ports, doors, etc.

The American Bureau of Shipping in 1986 published the "Guide for Building and Classing Offshore Racing Yachts" (ABS, 1994) with application to yachts up to 30.5 metres with plan approval. The Guide was updated in 1994 and in 1997 became limited to vessels having an overall length between 24 and 30.5 metres. After 1997 ABS stopped maintaining the Guide. All the main aspects of sailing yacht design are assessed: materials, details and fastenings, plating, internals, rudders and keels. The only areas on which no indications are provided is for the mast and rigging. Where the hull scantlings are concerned, the Rules in section 7 provide formulae and tables for the thickness calculation of plating; aluminium, steel, fibre reinforced plastic (both single skin and sandwich) and wood are considered. The same approach is assumed for the scantling of internal reinforcements. Compliance with this standard was required by the International Sailing Federation (ISAF) for yachts entering most offshore sailing races. In 2009 ISAF began requiring compliance with ISO 12215. For all those aspects not included in the Offshore Racing Yacht Guide, reference should be made to the "Guide for Building and Classing of Motor Pleasure Yachts" (ABS, 2000) for displacement and semi-planing yachts. Designers of large sailing yachts capable of sustaining high-speeds (in the planing regime) are referred to the "Guide for Building and Classing High Speed Craft" (ABS, 2001) for appropriate hull plating and internal structure scantlings.

The "Rules for the Classification and Certification of Yachts" of Bureau Veritas (BV, 2006) place a strong emphasis on sailing yachts. The philosophy for determining hull scantlings consists of presenting different criteria for the calculation of design accelerations and loads. Still water and wave loads are provided for mono- and multi-hull sailing yachts. Specific global loads acting on the hull and caused by rig tension are also included. Particular attention is devoted to bottom slamming loads, where the case of sailing yachts is specifically assessed, and the loads induced by the keel weight. Where the scantling formulae for plating and stiffeners are concerned the approach is the same for both motor and sailing yachts, the difference being already inherent in the determination of design loads.

Germanischer Lloyd, in their rules for "Special Craft" (GL, 2003), dedicate particular attention to sailing yachts. In chapter 2, yachts with a length greater than 24 metres are considered, while chapter 3 is dedicated to yachts and boats up to 24 metres. In this latter part sailing dinghies, sailing yachts and motorsailers are all considered. In the first section all the main dimensions and design loads are specifically defined for sailing yachts. The Rules provide hull loadings in terms of pressure on the bottom and side shells as a function of the ship scantling length; in the same way pressures on the deck and superstructures are also provided. For all the structural elements specific reference is made for sailing yachts. The scantlings of hull plating should satisfy particular characteristics of the shell laminates in terms of total glass weight. The section moduli of the transverse and longitudinal frames of the hull and deck structures are given for sailing craft and motor-sailers in very clear tables. Reinforced bulkheads are required in way of the mast together with an increase of floor modulus in the region of the ballast keel connection to the hull. Chapter 2 refers to motor and sailing yachts with a length between 24 and 48 metres in the first part and over 48 metres in the second. Design loads, in terms of pressure on the hull and on the deck, are provided with different longitudinal distributions for sailing and motor yachts, while the same scantling formulae are valid for both. Three different sections for steel/light alloy, composite and wood materials are provided. As in the previous cited chapter 3, reinforced bulkheads are required in way of the mast together with an increase of floor modulus close to the ballast keel. In the case of yachts with a length over 48 metres, depending on whether they are high or medium speed vessels, reference should be made to the High Speed Craft or Seagoing Ships GL Rules.

The RINa "Rules for Classification of Yachts" (RINa, 2007) consider the sailing yacht hull structure in the same way as for motor yachts, the only difference being the pressure loads calculated for displacement vessels. Rules applicable for craft under 12m are rare. However, a complete set of rules for small 6m and 12m S.I. racing yachts was published by RINa in 1984 (RINa, 1984). All the design aspects were considered from the material selection, up to the hull structure typology (transverse or longitudinal), keel-hull connection, outfitting and mast and rigging scantling.

3.4 Materials Selection Criteria

The primary criterion for hull material selection for the pleasure boat industry is reducing cost. Thus woven roving or mat E-glass fibres in iso- or ortho-polyester resins are the most common combination. Improved properties are achieved through higher strength and modulus fibres such as aramid and carbon. Similarly, increased fatigue resistance, higher shear strengths and reduced osmotic blistering properties are possible with epoxy and vinyl ester resins. When sandwich materials are chosen balsa wood or PVC cores are usually employed. The alternative metallic materials are marine-grade steel and aluminium alloys. Wood is still used in niche markets, often in combination with cold-moulded construction techniques. The main advantages and disadvantages of each material (except wood) are summarised in Table 3.

Table 3
Construction materials for hull structure

Material	Advantages	Disadvantages
FRP Composites	Lightweight. Easy to mould complex shapes Cheap, more so for series production. Ability to tailor properties. No painting (when gel-coated) or fairing (female moulds). Low wastage. No rot or corrosion. Low maintenance. Easy to repair. Non-magnetic. Low energy material.	Little plastic deformation to fail (for impact energy absorbtion). Low fire resistance, toxic fumes. Production working environment. Fatigue issues in high-stressed applications. Skilled labour source required for quality assurance.
Aluminium	Lightweight. Easy to work. Non-magnetic. High plastic deformation to failure	Expensive. Welding distortion. Costly to paint. Less readily available.

	relative to FRP (for impact energy absorbtion).	Requires heat insulation. Galvanic coupling. Fatigue. Can melt at temperatures seen in fires.
Steel	Cheap. Simple to fabricate. Easy to repair. Fire resistant. High plastic deformation to failure relative to FRP and aluminium (for impact energy absorbtion).	Heavy. Hard to shape. Welding distortion. Requires heat insulation. Corrosion. Galvanic coupling.

For higher performance vessels where weight or stiffness is a driving factor in the design, alternative reinforcements such as unidirectional or multi-axial fabrics may be preferred. In racing yachts materials selection is often governed by handicap measurement system (e.g. IMS, IRC) or class rules (e.g. ACC, IMOCA), or for a larger number of yachts, standards such as those given by classification societies (ABS, DnV, Lloyds) or the ISO. These often provide panel weight limits, limit fibre modulus and define minimum strengths. Aramid, aluminium or polyethylene honeycomb cores and pre-preg skins are widely used for performance yachts.

3.5 Structural Arrangement

The structural arrangements of sailing yachts vary significantly depending on the vessel size, its mission and the construction materials used. Small vessels less than 10 metres in length typically rely on the hull skin and deck for most of the structural support while yachts longer than 24 metres use a system of bulkheads, ring frames and longitudinals to support the skins. An inshore vessel may have no bulkheads while ocean-crossing vessels may have multiple watertight bulkheads. Traditional vessels constructed of carvel or lapstrake wood used a large number of frames to support the caulked planking and frame spacings of less than 0.3 metres were not uncommon. At the other extreme, modern composite yachts designed using a monocoque hull may have only two or three ring frames and limited additional structure to withstand local loads.

Primary structural consideration is naturally given to the watertight integrity of the hull and deck, although this does not normally dictate the structural arrangement, except for the intrusion into the interior volume by the trade-off of hull skin thickness versus frame spacing and size. The primary structural considerations affecting the arrangement are:

- Rigging loads and components
- Keel support
- Engine support
- Steering system
- Accommodation
- Watertight bulkheads

The two with the greatest impact on the structural arrangement are the rig and the keel. A typical sailing yacht has a single mast supported by tensioned stays and shrouds. When the vessel heels the tension in the windward shrouds increases and the compression loading of the mast tube also increases. This large point load is traditionally dissipated to the hull shell through a rigid longitudinal mast step. On small or lightly loaded craft the mast step may sit directly on the hull plating similar in design to a centre vertical keelson. On larger craft the mast step sits on substantial floors. If the mast is deck stepped rather than keel stepped a compression post takes the load from the deck to the keelson. Examples of the impact of these loads on local deformations are shown in (Larsson and Eliasson, 2007) for large ocean racing yachts and by (Miller, 2000) for a coastal racer.

Figures in the rig section show that the lower diagonal shrouds impart a transverse compression component in the deck and both shrouds place a large shear load on the hull. These are typically addressed through the use of a substantial main bulkhead in close proximity to the mast. On small craft the main bulkhead and mast step may be combined. Longitudinal rigging loads are typically supported by the hull and deck, with deck girders rarely used unless panel buckling is a concern.

Keel support structural arrangement is strongly influenced by Classification Society standards which generally require a minimum of three substantial floors extending out at least to a pair of longitudinals and often beyond, to taper near the design waterline or continuing on to form ring bulkheads. This primary set of longitudinals often taper toward the centreline behind the keel to transition to engine beds on craft under 12 metres. Forward, the longitudinals support the mast step floors and reinforce the hull shell in the slamming area.

Production considerations influence the structural arrangement on series built vessels in that joinerwork and furniture are often moulded separately from the hull and are lightly joined to the hull using adhesives. In custom performance yachts the furniture and joinery can be integrated into the structure resulting in a significant weight saving. Figure 6 shows the structural arrangement of a 24-metre custom performance cruising yacht built in 2005 as analysed in a finite element model. Forward watertight bulkhead and the substantial keel floors are evident. Composite structural joinery work panels support the hull and deck and much of the forward furniture is designed to reinforce the hull in the slamming area.

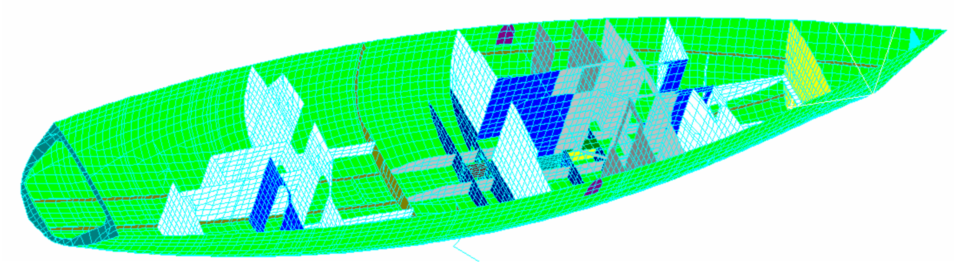


Figure 6: Structural arrangement of 24-metre lightweight cruising yacht.

A growing trend is toward monocoque construction to reduce weight, construction costs and interior encroachment. Figure 6 shows the structural arrangement of a 25-metre racing yacht analysed in a finite element model. Substantial bulkheads forward and aft of the mast step withstand rigging loads three times higher than that of the cruising yacht in Figure 7. The aft bulkhead additionally supports a keel whose righting moment is also three times larger than the cruising yacht's. Partial bulkheads outboard of the keel structure support genoa tracks and small, lightweight longitudinals and ring frames forward resist panel deformation. Deck girders are required to handle the large deck compression loads and the small bulkheads aft support the backstays and mainsheet track.

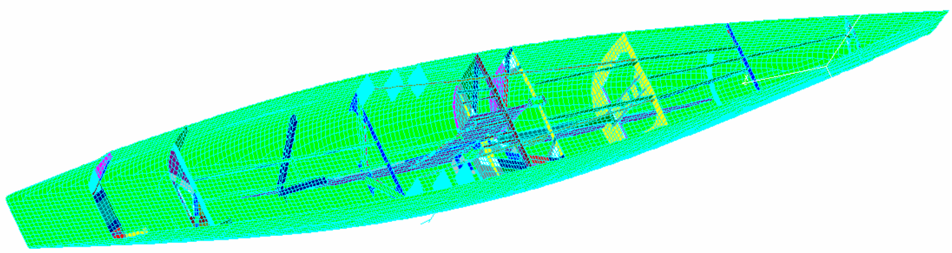


Figure 7: Structural arrangement of 25 metre racing yacht.

A typical bulkhead in way of the mast is illustrated in Figure 8 with the detail for a composite chainplate in Figure 9.

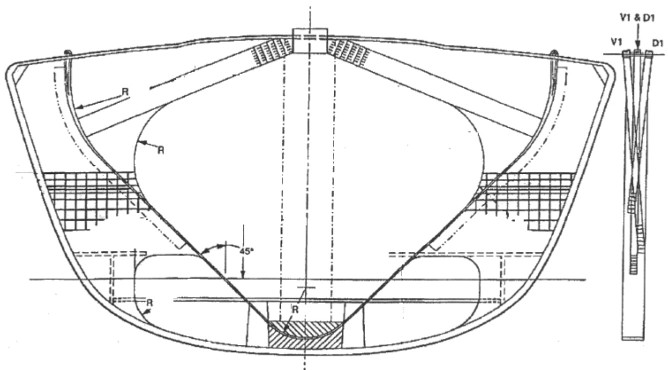


Figure 8: Example of V-strap mast bulkhead drawing (Reichel/Pugh Max -Morning Glory).

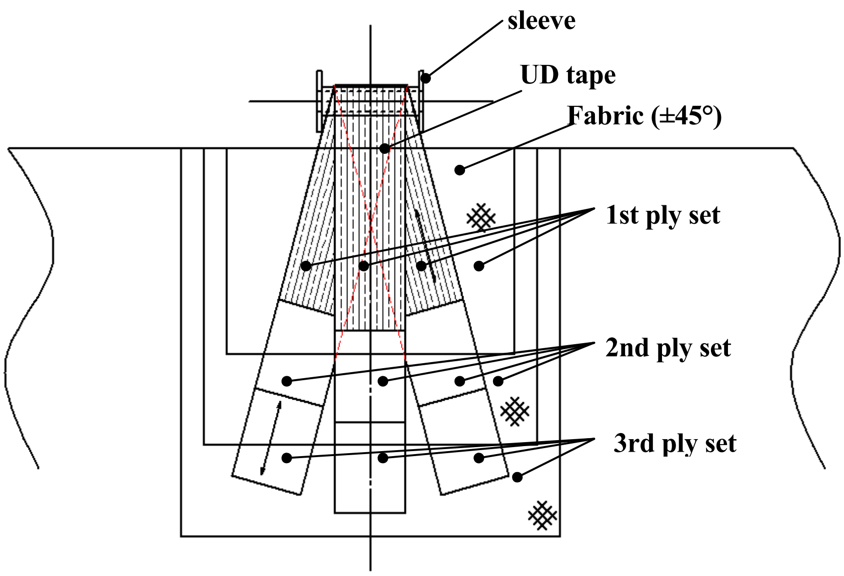


Figure 9: Schematic of composite chainplate.

3.6 Production Methods

As is well known the most common material for sailing yacht construction was, for many years, wood. Many yachts constructed of wood continue to survive thanks to the unique characteristic of this material, which allows easy repair. Due to this aspect there are many masterpieces of the yacht building art sailing at sea. The word ‘art’ is suitable in this case because the construction procedure of a sailing yacht often relies on the skill of local workforces rather than on modern shipyard construction techniques. With application of new bonding products and procedures, coming from composite material production, wood is again utilised in the construction of innovative boats with laminated construction being allied to epoxy resins. Thanks to the elimination of mechanical joints and bolts/screws this technique produces very light shells, made stronger by the presence of epoxy resin.

Sangermani Shipyards in Italy implemented this technique, studying the effect of carbon cloths inserted between layers of red cedar wood. The shipyard produced a 25 metre schooner, called Quarta Santa Maria, in 1995 and other smaller sailing yachts with the same technique. A further proof of the quality of this method is represented by the sailing yacht Sheherazade which, launched in 2003 from Hodgdon Yachts Shipyards on the coast of Maine, U.S.A. and having an overall length of 47.10 metres, is the largest yacht constructed in this manner.

The production of sailing yachts with steel and aluminium alloy is used for yachts of a large size, typically over 40 metres in length. It is possible to find some exceptions but, in general, these are represented by racing yachts (in aluminium) and training ships (in steel). The facilities and techniques used to construct such vessels are, in general, very similar to those employed for merchant ships and motor yachts, the only differences being the hull shape and the stiffener sections.

It is important to underline that the biggest sailing yacht in the world EOS, a 92.9 metre Bermudan rigged schooner, was built in aluminium alloy by Lurssen Shipyards (Germany) in 2006. Another very large sailing yacht, Athena, launched by Royal Husman Shipyards in 2004, was also built in aluminium. For several years the largest steel sailing yachts have been built by Perini Navi, the 88 metre ‘Dynarig’ schooner Maltese Falcon launched in 2006 represents a significant example from this shipyard.

For normal yachts of a medium size and constructed from FRP composite materials the traditional procedure of laminating in a female open mould is still used by the majority of shipyards. For polyester/glass composites a normal hand or spray lay-up technique can be used.

In a typical hand lay-up, reinforcements are laid into a mould and manually ‘wetted out’ using brushes, rollers, or through other means. The part is then cured, cooled and removed from the re-usable mould. This production method is a very economical process and has a low investment; it can be used for complicated shaped pieces and the laminate thickness is adaptable. The disadvantages of hand lay-up are that the final quality depends heavily on the skill of the personnel and, because of its open mould nature, the effects on the local working environment are proven to be dangerous for human health.

The fibreglass spray lay-up process is similar to the hand lay-up process but the difference lies in the application of the fibre and resin material to the mould. Spray-up is an open-mould composites fabrication process where resin and reinforcements are sprayed into a mould. Workers ‘roll out’ the spray-up to compact the laminate. Wood, foam or other core materials may be added, and a secondary spray-up layer embeds the core between the laminates. The advantages of this production method are similar to those of hand lay-up. However, it is not suitable for making parts that have high structural requirements. It is also difficult to control the fibre volume fraction as well as the thickness, which highly depend on operator skill. The process offers a good surface finish on one side and a rough surface finish on the other. The process is not suitable for parts where dimensional accuracy and process repeatability are prime concerns, and styrene emission is again a concern.

An improvement on the hand lay-up method is to use a vacuum bag placed over the laminate, sealed around the edges to the mould and evacuated using a vacuum pump to force excess resin out of, and to consolidate the laminate. However, this technique is normally used in conjunction with pre-preg laminates, where the fibres are pre-impregnated with resin in a very controlled manner by the materials supplier. These materials must be kept refrigerated until they are placed on the mould and may be cured at elevated temperatures by the boat builder.

Resin infusion (RINa, 2006) builds upon these principles, providing further improvements to the lamination process. The technique uses vacuum pressure to drive resin into a laminate. Reinforcement materials are laid dry into the mould, covered with peel-plies, breather materials, vacuum distribution mediums and finally a vacuum bag and the vacuum is applied before resin is introduced. Once a complete vacuum is achieved, resin is sucked into the laminate via carefully placed tubing (Figure 10).

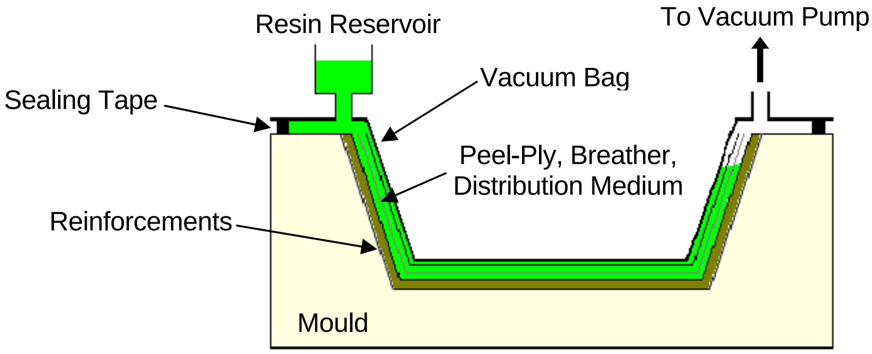


Figure 10: Schematic of Resin Infusion Production Process

‘Resin infusion’ is in fact a general term, and the process as used in yacht production, may also be correctly referred to as ‘Vacuum Infusion’ or ‘SCRIMP’ (a specific proprietary method). However, there is some confusion in terminology with Resin Transfer Molding, or ‘RTM’, (in which dry fibres are injected with resin under high pressure in a mould of very stiff male and female parts) and Vacuum Assisted Resin Transfer Moulding, or ‘VARTM’, (where RTM is assisted by a vacuum applied to the stiff mould prior to injection) somewhat erroneously being used to describe the resin infusion process used in boat building.

The production of composite yachts is moving rapidly towards these ‘closed-mould’ production techniques, especially resin infusion. This change is mainly driven by the fact that closed mould techniques can largely eliminate the undesirable working environment associated with hand lay-up and spray-up, a very important requirement given ever more stringent environmental regulations. The other main advantage is the higher and less variable laminate quality achieved using infusion. For series production or large components infusion also results in lower costs, but for smaller, one-off products, and especially whilst gaining experience in the technique, cost savings are not large.

The benefits of using the infusion process are:

- Greatly reduced emissions
- Better fibre-to-resin ratio
- Less wasted resin
- Very consistent resin usage
- Unlimited set-up time

- Cleaner working environment
- Ability to achieve from 0.5mm to 90mm laminate thickness
- Ability to mould complex structural and hollow shapes
- Uses only low pressure (moulds do not have to be excessively stiff and existing moulds may be used)
- Inserts may be incorporated into mouldings
- Selective reinforcement and accurate fibre management is achievable
- Components will have good surface finish on both sides (Professional Boatbuilder, 2008)
- Sandwich structures may be laminated in one hit.

However, infusion is not without its drawbacks and it is important to consider the following points:

- Complicated set-up: both vacuum tubes and resin inlet placement will be critical.
- Easy to ruin a part: typically once infusion begins it is difficult to correct any errors.
- Trial and error: due to the complexity and ease of error, resin infusion should be viewed as a trial-and-error process. The best approach is to carefully document each attempt in order to learn from each trial and to practice with small quantities and inexpensive materials before undertaking full-scale projects.

When the weight of a component is critical (e.g. the deck, superstructure and bulkheads) it is common to use a sandwich structured composite. This is a special class of composite materials that is fabricated by attaching two thin, but stiff, skins to a lightweight, but thick, core. The infusion process can be used to fabricate a sandwich laminate in one procedure, eliminating the need to bond the skins to the core. The core material is normally low strength material, but its higher thickness provides the sandwich composite with a high bending stiffness yet having overall a low density.http://en.wikipedia.org/wiki/Image:CompositeSandwich.png Open- and closed-cell structured foam, balsa wood, syntactic foam and composite honeycomb are commonly used core materials. Glass or carbon fibre reinforced laminates are widely used as skin materials. Sheet metal is also used as a skin material in some cases.

Until the 1980's sailing yachts typically had a single skin hull with longitudinal reinforcement and a sandwich deck. Some ship yards producing high performance cruising or racing yachts began to use the sandwich technology for the hull of vessels. Today a great many sailing yachts are built entirely in sandwich structures to reduce their weight and increase performance. It should be mentioned that the sailing yacht Mirabella V, with a length of 75.2 metres, is the largest vessel in the world built in composite material using the sandwich technique for the complete hull. The outer skin of Mirabella V is just 7mm thick (out of a total hull thickness of 63mm) and is made of layers of stitched bi-axial material which absorbs resin well and helps prevent show through. A layer of Herex foam was vacuum-bagged to the outer skin before the inner skin was applied.

Without doubt a large majority of sailing yachts are built in composite materials. Owing to the wide variety of resins and reinforcements in use, different production procedures need to be applied. The necessity for environment and health protection, together with product quality improvements, requires a continuous development in production methods.

4. MAST AND RIGGING

4.1 The Arrangement

Mast and rigging represent for sailing boats the structural system which support the forces developed by sails and control their optimum shape and trim; the boom mainly controls the attack angle of the main sail and it is subjected to lower loads.

Masts and booms are defined as “spars”, stays and shrouds form what is known as “standing rigging”, that is the category of equipment which holds the sails, while the term “running rigging” groups other equipments (halyards, sheets) which have the function of continuously adapting the sail configuration to the changing wind conditions.

Excessive rig deformation, allowed by a non-sufficient system stiffness, has the negative effect of changing the expected pressure distribution on the sails, decreasing the propulsive efficiency of the boat. On the other hand a certain amount of flexibility is necessary to allow the mast to be bended in order to allow the sail to have a proper shape relatively to the sailing condition. As a consequence, mast and rigging should have “reasonably resistant” section.

Because the mast is the leading edge of the mainsail, a large section has the effect of creating a high pressure area behind the mast, neutralizing a significant portion of the main sail, thus reducing the total propulsive force and rotating it athwartship. In addition, the rig system has a very high centre of gravity and an increase of its weight has negative effects on stability and on the capability of the boat to “stand” the wind. This can be counterbalanced only by increasing the keel weight, and so the total displacement of the boat.

Excluding unstayed masts which are predominantly used on vessels under 10 meters, sailing yacht spars are sustained by a three-dimensional rigging system made up by shrouds in the transverse plan of the boat and stays in the longitudinal one.

Stays and shrouds are connected to the boat in correspondence of proper reinforced hull points. Common locations for headstay and backstay are the bow and the stern, while shrouds are secured athwartships the mast by chainplates. Both shrouds and stays are connected to the top of the mast in case of a masthead rig, and below the masthead in a fractional rig. Diagonal shrouds are connected near the spreader roots and, in oder to avoid higher compressive loads, angles below 10-12° are not recommended.

In the longitudinal plane space availability allows the stay angle to open up to 30° and more while, in the transverse plane, maximum shroud angles are limited by the reduced hull breadth.

To avoid long unsupported spans that may cause buckling phenomena, masts are then fitted with spreaders, in a number to keep the shroud angle over 10°; the highest spars can have up to 6 spreader levels. Shrouds can be continuous or discontinuous; the continuous solution consists of full-length shrouds, with constant section, from the mast attachment point down to the chain plates. The discontinuous solution consists in separate spans from two sets of spreaders connected at the spreader end with mechanic links.

In the longitudinal plane aft of the mast, the mainsail requires unconstrained space so that it becomes difficult to set support points for the mast at intermediate heights. The way the mast is supported depends on the type of rig: in a masthead sloop the mast is sustained by a forward headstay and an aft backstay, while in a fractional sloop the mast is sustained by a forestay and, aft backstay attached to the top of the mast and by running backstays attached in correspondence of the forestay. In the cutter configuration the mast has an additional support ahead, a babystay and, optionally, running backstays after. The presence or not of running backstays depends on the nature of the yacht: in a cruise yacht it is preferable to avoid the runners in order to make the boat easier to be handled, whilst it is necessary to set them on a racing yacht in order to better trim the mast and achieve best performances. For all the considered configurations spreaders can be set in line with the mast axis or aft swept in order to give ad additional support in the longitudinal plane. Aft sweep of spreaders greater than 15° often negates the need for runners.

The type of arrangement heavily influences the performances of the boat and the strength of the mast as well. So it is very important to consider adequately the proper configuration in view of a verification of spars and rigging.

Masts can be either deck-stepped or keel stepped. Deck stepped masts are used in boats which need to be trailed or to pass beneath low bridges on channels, because masts can easily be raised without needing a crane. For large sailing yachts keel stepped mast is preferable, mainly for its higher resistance with regard to bending, compression and buckling. This is due to the higher efficiency of the lower end constraint and to the contribution of the through-deck passage, which can be considered an additional constraint. On the other hand the mast below deck represents a considerable encumbrance for cabin layout and it heavily influences the interior layout.

4.2 Materials Selection Criteria and Production Methods

The traditional material for spars (masts, booms and spinnaker poles) was wood; different types of wood were used: sitka spruce, douglas fir and oregon pine. The construction procedure was very complex, especially in the case of high masts, when it become necessary to assemble and work many parts. This activity is still in progress in some shipyards specialized in the restoration of classic sailing yachts. As an example, for a 25 meters yacht, up to 4 groups of planks in length times 10 in breadth are necessary to re - build the mast.

During the 1960's wood was eclipsed by aluminium due to its greater durability, higher specific properties and lower cost. Aluminium alloys, generally 6000 series, are commonly utilised, with magnesium and silicium that give to the material high mechanic characteristics and good resistance to corrosion in the marine environment. For short, economical masts, 6063 alloy is used, 6061 type for high quality masts and 6082 type, which is the most expensive one, for racing yacht masts.

Table 4
Aluminium alloys adopted for sailing yacht spars.

Aluminium alloy	σ0.2% [MPa]	σu [MPa]	εu	HB	E [MPa]
AA 6063	150	195	12%	80	69 000
AA 6061	235	255	8%	80	69 000
AA 6082	255	305	10%	90	69 000

(σ0.2%: stress at 0.2% elongation, σu : ultimate stress, εu: strain, HB: Brinell hardness, E: Young's modulus)

An imperative requirement for a mast section is to provide adequate inertia with minimum dimensions in order to assure good buckling resistance and low interference with the mainsail. Mast profiles are obtained by extrusion in a wide variety of section shapes, with longitudinal inertia Jyy much greater than the transverse one Jxx. Some of them, as an example, are listed below (see in Figure 11).

- oval sections, used for small-medium size cruising yachts without particular performance requirements. The ratio between the two diameters is about 1.5 while the ratio JYY/JXX ranges between 1.8 and 1.9.
- bullet sections (or "D" sections) are employed for high efficiency rigs. The ratio between the two diameters is about 1.6÷1.9 and the JYY /JXX ratio for these types ranges from 2.5 up to 3.
- open sections are used when a mainsail reefing system is to be set up. The ratio between the two diameters is about 1.8÷2.0 while the JYY /JXX ratio ranges between 2.5 and 2.8.

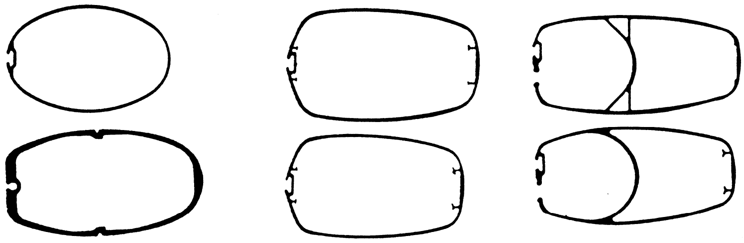


Figure 11: Aluminium mast section shapes: oval, bullet, rectangular and open (Claughton et.al., 1998).

The most part of aluminium masts have constant section along its length; in the case of big and/or high performance yachts it is a common practice to reinforce the mast base and to taper the top. The first action is performed by bolting aluminium strips inside the fore and aft part of the section to increase longitudinal inertia; the more effective alternative consists in introducing a sleeve inside the mast and to bolt or rivet them together. The same method is employed to create masts longer than 18 metres jointing two profiles. In this case a coupling profile is introduced in the mast for two - three diameters in length and the two parts are bolted together.

The top of the mast is tapered cutting a strip of material from the side of the profile of increasing width. Then the two edges are welded together obtaining a decreasing section towards the masthead. This simple procedure allows a reduction in weight and makes the top of the mast more flexible.

Carbon masts began to be used in the early 1980's, initially in racing dinghies, and then the America's Cup and Admirals Cup yachts. In two decades since their first use carbon fibres are not as widely used as one might think; in fact they are only considered when weight is critical and are therefore limited to racing yachts or performance oriented cruising yachts. This is an area which has evolved greatly in recent years, as innovative materials and designs have been explored. Monolithic and sandwich structures have been used. Dimensioning of composite masts is complex and requires analysis of global and local buckling, aerodynamic considerations and evaluation of the strength reduction due to many attachments and geometrical variations. High modulus carbon fibres including M55 and Pitch have been used but the most popular choices are intermediate modulus fibres such as M46 for racing yachts or standard modulus fibres such as T300 for cruising yachts. Software now exists to assist in material selection like, as an example, SIMSPAR code (Pallu, 2008). Carbon masts consist of mainly longitudinal unidirectional fibres (over 80%) with some at ±45° and 90°, in an epoxy resin matrix. Most composite masts are manufactured in two half shells with the primary shell reinforced with local buildups at hardware attachment points. Preimpregnated fibres are laid up by hand in a female mould and cured at 120°C in an oven or autoclave. The two parts are then bonded together. An alternative fabrication process involving braiding of fibres around a mandrel produces a single part mast. A large number of finishing operations are then required, including machining of holes to fix the mainsail track, rigging attachments and spreader features. Note that the two part masts must also require detail attachment work in addition to the work involved in the bonding of the two sections.

Therefore a carbon mast can be built with increased strength in the direction of the principal loads. For optimum sail shape the bend of the mast is very important, as the bend, along with other factors, directly contributes to the sail's draft depth. As the vessel becomes overpowered greater mast bend flattens the sail, and since a carbon mast can be manufactured with precisely controlled orientation of fibres it is possible to create a mast which has the correct bending characteristics. Additionally the inherently easier shape tailoring of a laminated structure provides for optimized aerodynamic or structural shaping throughout the length. This is an important advance in technology, complement this with new sail technology and they form a superior aerodynamic shape that could ever be achieved with an aluminium mast and polyester sails. A review of carbon masts construction is presented in Hall, 2002. A top example of this technology is represented by the mast of Mirabella V, the largest sloop of the world. Her carbon epoxy mast is 100 meters long, with five sets of spreaders, a section of 1600 mm in the longitudinal plane and a maximum thickness at the step of 40 mm.

For America's Cup boat masts, high strength intermediate-modulus type carbon fibre (Fibre Modulus=295GPa, Tensile Strength=4400MPa) is used in accordance with the appropriate property limits of the America's Cup Rules. As an example, the mast for the Nippon Challenger 1995 was formed in two pieces, front side and back side, then bonded into a unique piece (Figure 12). The 2000 challenger mast was built by an integral moulding with a female mould and a pressure bag. This method requires a very high strength of the mould as a good quality can be attained just by applying a high pressure by a vacuum bag; it was very effective and it does not need any auto-clave or assembly procedure. The female mould was built from aluminium alloy with a similar technology of aluminium mast building.

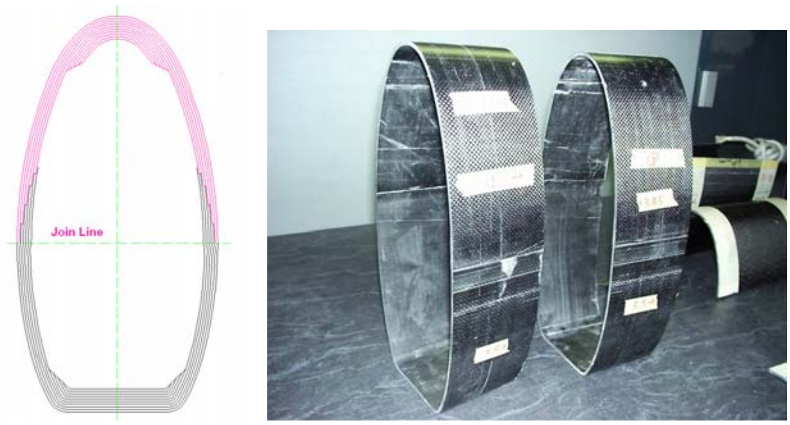


Figure 12: Two pieces carbon mast (1995 America's Cup Nippon Challenger).

Further developments in masts could come from the use of new matrix materials and new fibres, such as PBO (para-phenylene-benzobisoxazole), which could be used to increase the properties of the mast.

Standing rigging, traditionally in ropes from natural fibres such as hemp, manila or sisal, is today generally in steel wire rope (1x19) on small yachts. For racing yachts and superyachts Nitronic 50 stainless steel is being replaced by high performance synthetic fibres, notably PBO and aramid. The use of continuous fibre slings results in lighter cables. Carbon fibre rigging is also under development. For running rigging polyester is the standard choice, more expensive fibres such as HMPE (Dyneema), aramid or Vectran are used for halyards.

4.3 Loadings

It should be underlined that, in the last decade, significant progress has been made in the field of aerodynamic and hydrodynamic load analysis, thanks to some prestigious international competition such as the America's Cup and Admiral's Cup. Many problems related to the forces generated by sails have been faced by developing powerful numerical software able to take into account a large number of geometric and physical variables.

Nevertheless some problems remain like, as an example, the behaviour of rigging under wind gust, the dynamic loading on the mast caused by the boat movements in rough sea and the pretensioning loads induced by initial rigging trim. These aspects are currently under investigation but, up to now, it is difficult to have reliable results. The consequence of these, and other, uncertainties is that the range of safety coefficients becomes very wide and it is very difficult to choose the correct one. Too much severe loads will result in very safe but low performances rigging, too much optimistic loads will result in good performances but unreliable rigging. The correct choice should individuate a compromise able to obtain a good rigging system with "reasonably good performances" and "reasonably safe configuration". This choice does not depend only on technical aspects but also on the skill of the crew: it is obvious that the safety level of a racing yacht cannot be the same of a cruise one.

A review of methods used for the calculation of mast and rigging design loads is presented in the following, covering the development from the very old empirical ones, up to present numerical methodologies.

The loads applied to the mast are mainly due to the forces developed by sails, by pretensioning loads and by the hydraulic jack used to raise the mast. An approximate evaluation can be performed on the basis of a uniform pressure distribution as a function of weather conditions and wind speed (Marchaj, 1979).

A more rigorous approach, although roughly simplified, consists in considering the equilibrium between hydrodynamic forces acting on the hull and the aerodynamic forces developed by the sails. The amount of the propulsive effect generated by sails depends on a number of factors such as: the area and geometry of sails, the apparent wind velocity and the angle of incidence of sails. The resultant of sails forces FT can be decomposed into lift L (normal to the apparent wind direction) and drag D (opposite to the apparent wind direction) and expressed in terms of non-dimensional coefficients CL and CD. Lift and drag can be measured in the wind tunnel during experimental tests on scale models and reported in polar diagrams as a function of the angle of incidence α.

The total force FT can also be decomposed into two other components: the driving force FR in the direction of the boat's course and the heeling force FH perpendicular to the boat's course; also in this case non-dimensional coefficients CR and CH are defined.

To compute the load exerted by sails on the mast it is then necessary to know the coefficients CL and CD or CR and CH; a great deal of experimental data on sails has been collected by researchers in wind tunnel tests and some of them are available in literature, such as those published by Marchaj (1962, 1964) or the data collection gathered on board Bay Bea yacht (Kerwin et. al., 1974).
The sail forces FR and FH can also be determined by considering the hydrostatic properties of the hull in heeled conditions. The heeling moment MH caused by the action of the wind on sails is balanced by the righting moment MR rising when the boat heels. The righting moment for an angle of heel θ is equal to $\Delta \times GZ\theta$ where Δ is the displacement of the yacht and $GZ\theta$ the righting arm. The side force FH can be determined as follows:

$$F_H = \frac{\Delta GZ_\theta}{h}$$

where h is the vertical distance between sails' centre of effort (aerodynamic) and hull centre of lateral resistance (hydrodynamic).

From the cross curves of the hull it is possible to know exactly the force necessary to heel the yacht of an angle θ; this will be the transverse force developed by the sails in a quasi-static condition. Assuming proper sail coefficients at the design heel angle θ, the apparent wind velocity and the driving force FR can be determined.

The starting point for the designer is then to determine the maximum heel angle θ to be assumed for the calculation. For little and medium size sailboats the reference heel angle for mast and rigging scantling is typically 30°. In the case of big sailing yachts this could be too large and might lead to excessive mast section dimensions; thus a maximum heel of 20-25° is often assumed.

Once the driving and heeling forces FR and FH have been calculated and subdivided between mainsail and foresail, the next problem to solve is how those forces should be applied on mast and rigging. In a simplified approach it can be assumed that the mainsail transmits to the mast a distributed load along its length. The simplest way to apply this load is by a triangular shape as shown in Figure 13a. Taking into account that the pressure on the upper part of the sail is greater, owing to the higher wind velocity, a trapezoidal distribution (Figure 13b) would be more suitable. According to lifting line theory the pressure follows an elliptical distribution because of the vortex rising at the upper and lower sail bounds (Figure 13c). The actual pressure distribution will vary dynamically depending on aspect ratio, twist and sheet tension. For application to a finite element model, this type of distribution can be well approximated by a step distribution as shown in Figure 13d. Such a distribution of the load is conservative towards the bending moment on the mast because the centre of application of the resulting force is higher than other ones.

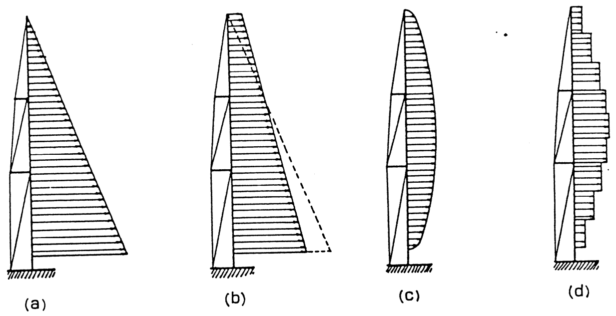


Figure 13: Distribution of mainsail load on mast: (a) triangular; (b) trapezoidal; (c) elliptical; (d) step varied (Claughton et.al., 1998).

As far as the foresail is concerned the total force can be split between the forestay and the jibsheet. The percentage depends on the tension in the halyard but it is reasonable to consider that 20% is supported by the sheet and the 80% by the jibstay and, consequently charged on the masthead. The force on the masthead depends on the tension in the jibstay and it is a function of the maximum jibstay deflection. The jibstay tension can be estimated considering the deformed shape of the stay to be a very tight catenary supporting a distributed load along its length. To know the tension in the jibstay, it is necessary to impose a minimum, reasonable value for the maximum deflection. It is sometimes argued that the curvature of the forestay could cause a stagnation effect on the mainsail and thus consequently decrease the propulsive force component FR. In order to reduce this effect it is a common practice to pretension the stay as much as possible increasing the compression and bending stresses on the mast. In current practice, it can be assumed a maximum stay deflection between 2 and 5% of the jibstay length.

There are other loads to consider such as those transmitted by boom, the compression at mast step by an hydraulic jack, the pretensioning of stays and shrouds and the tension of halyard. In the case of a linear analysis maximum values of considered loads should be applied to the model. The results of the calculation will be analysed in terms of stresses and displacements. For what the displacements are concerned it is a common practice not to allow displacements at the top of the mast higher than 2% of the total mast height.

To calculate the pressure field developed by the wind on sails of different shapes in upwind condition, even interacting each other, numerical methods based on lifting line or lifting surface theories (Milgram 1968, Greeley et.al. 1989, Jackson 1984) are now available.

Nowadays modern methodologies allow designers to perform more sophisticated analyses. Using CFD codes (Computational Fluid Dynamics) it is possible to estimate the flow around the mast and the interaction between sails and standing rigging, obtaining more precise information about loads. It is essential to model the totality of the fluid-structure interaction in order to accurately determine the loads.

Nevertheless all described methods require validations by experimental or real scale measurements. Some researchers in the past instrumented sailing yachts to collect load data on mast, shrouds and halyards (Enlund et.al., 1984). More recently, Hansen et.al. (2007) presented an investigation on sail forces measurement in wind tunnel and on board a full scale sailing boat.

These days some shipyards producing very large sailing yachts feel the necessity to achieve a more detailed knowledge of loads acting on the masts and rigging by implementing permanent instrumentation on their ships. A significant example here is represented by the instrumentation installed on the Perini schooner "Maltese Falcon" and described by Roberts and Dijkstra (2004). The same activity is under course in the Department of Naval Architecture of the University of Genova where a new measurement system has been realized and it will be installed on another Perini Navi sailing yacht (Rizzo & Carrera, 2006).

4.4 Structural Responses and Methods

Standing rigging can be considered as a unique, balanced, structural system which should withstand loads transmitted by sails: mast and spreaders are designed to support compression stresses, stays and upwind shrouds support tension stresses. Chainplates finally distribute the shroud tension on side shell and frames. Similarly, stays should be secured to the bow and stern by properly reinforced connections; vertical components of stay and halyard tension induce high bending moment on the hull which mast be accurately considered in the evaluation of longitudinal strength of the canoe body. In a past investigation on the Italian America's Cup 12 m, real scale tests showed that the only rigging pretensioning could cause a hull displacement amidship of about 6 mm (Boote et.al., 1985). A similar order of magnitude was found on J/24s (Miller, 2000).

A mast's structural model is a typical beam-column, loaded by axial and lateral forces acting in the longitudinal and transverse boat plans. While the mast supports all the compression, bending is balanced by stays in the fore-and-aft direction and by shrouds athwartship. Stays and shrouds also behave as mast constraints, shortening the unsupported length. The structural design of masts is traditionally faced separately in the longitudinal and transversal directions for the sake of simplicity.

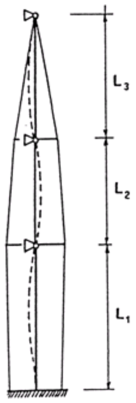


Figure 14: Mast with two spreader orders: buckled shape dashed (Claughton et.al., 1998)

In the transverse direction it is assumed that the shrouds divide the total height of the mast into panels of reduced lengths. The buckled shape of the mast then flexes in correspondence of the spreaders (see Figure 14). Each panel is considered simply supported owing to the presence of shrouds. A keel stepped mast should be fixed at the lower end in correspondence of the bottom (in case of deck-stepped mast a pin constraint is advisable) and pinned at the upper extremity. For the sake of conservativeness the contribution of deck constraint is neglected. In the longitudinal plan, the mast constraints are represented by stays. However, their noticeable length allows mayor displacements of the mast, which cannot be considered perfectly supported. Several hypotheses can be assumed, as synthesised in Figure 15.

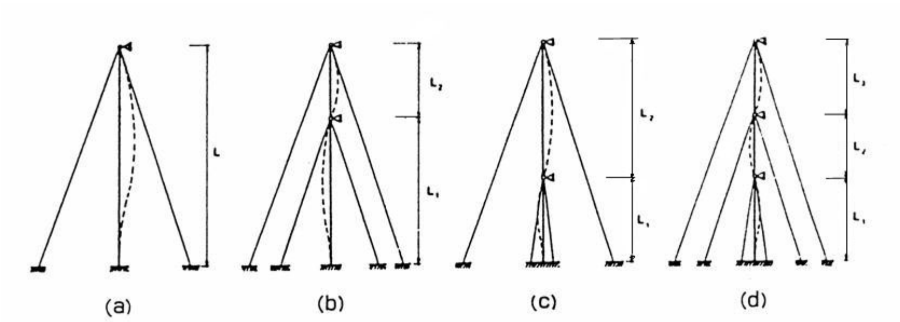


Figure 15: Buckled shapes of mast in the longitudinal direction: (a) mast with forestay and backstay; (b) mast with babystay and running stays; (c) mast with fore and aft lower shrouds; (d) totally supported mast (Claughton et.al., 1998).

It is a matter of fact that the case (a) is the most conservative condition and the case (d) is the most optimistic one; an acceptable compromise comes from considering an intermediate situation between (a) and (b-c) cases.

For the scantling of mast and rigging, several simple methods exist in literature and others are proposed by Classification Societies. Probably the most widely used is that known as Skene's method (Kinney 1962, Henry and Miller 1963, Miller and Kirkman 1990). Essentially the known hydrostatic righting moment of the yacht is equated to the heeling moment due to sails. Since the mast is in compression and the shrouds are in tension, the heeling moment is assumed to equal the vertical chain plate load times the horizontal distance between the center of the mast and the chain plate for the shrouds. The compressive load PT at the basis of mast is computed from the righting moment of the hull at 30° heel. To obtain the design compression in the mast P, the basic chain plate load is then multiplied by correction factors to account for the dynamic loads, halyard tension and stay pretension.

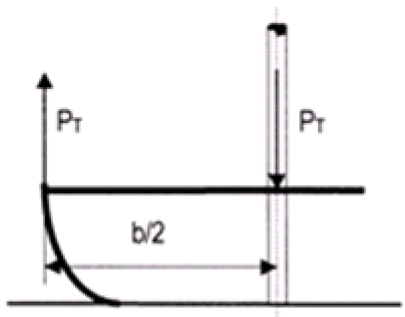


Figure 16: Lower shroud spreading

$$P = 1.85 P_T \quad \text{where} \quad P_T = \frac{1.5 \cdot RM_{30}}{b/2}$$

where (from Figure 16):

RM_{30} = righting moment at 30° heel;
b/2 = lower shroud spreading;
1.5 = coefficient taking into account heels greater than 30°;
1.85 = coefficient for shrouds and stays trimming.

A similar approach is used for the mizzen mast in multi-mast rigs. The load on the mizzen is some fraction of the main mast load; Henry and Miller (1963) use 1/3. The shroud design and stay loads are determined as a percentage of the chain plate load with similar appropriate safety factors. The percentages were developed from simple static equilibrium for a truss and actual shroud tension measurements while sailing. The head stay load is assumed equal to the largest shroud load. The backstay is proportioned to the head stay load based on distance to the mast. The spreaders are loaded with the equivalent shroud loads taking all angles into account. While Henry and Miller (1963) give values for all the empirical load factors and safety factors, modern spar manufacturers have developed their own sets of numbers for different types of designs such as racing and cruising boats.

The obtained compression values are then compared with the Eulerian buckling load calculated for the actual properties of the mast. It should be noted that the buckling analysis is performed considering the total compressive load applied at the upper extremity of the mast, while, in the real situation, the axial loads are different on each panel.

Kinney (1973) presents both a simplified method, that is essentially given in the previous paragraph, and a more detailed one. This second procedure assumes pressure acting on the sails of 1 lbs/ft2. The jib load is concentrated at the forestay mast attachment point, the main sail load is evenly distributed along the mast. The loads in the stays are then computed assuming the shrouds form a truss to support the side loads of the sails. The total design mast compression is found using the resolved shroud loads, spreader loads, and additional compression due to halyards, sheets and weight of the sails, boom, mast and rigging.

A different empirical method, but still based on the yacht righting moment, is presented by Larsson and Eliasson (2007). It is based on the standard engineering practices as presented in the Nordic Boat Standard (NBS, 1990). Again, all the loads are based on the righting moment of the yacht at 30º of heel including any increase in righting moment due to crew on the rail, water ballast, swing keel, etc. Two independent loading cases are considered for the shrouds:

- the first one is a concentrated load at the top of the shrouds that will heel the yacht to 30º;
- the second also heels the yacht to 30º, but the load is applied at the centroid of the reefed main area. This concentrated load is then appropriately proportioned between the boom, spreaders and the top of the upper shroud.

Assuming mast, spreaders and shrouds to form a truss system, the design load can be achieved together with appropriate safety factors. The loads in the stays depend on the type of rig but, basically, they are based on the righting moment at 30º. The mast compression load is 1.5 times the chain plate load. Spreader loads are based on the transverse component of the design shroud force. Design loads for the boom, based on the righting moment at 30º, and the location of the main sheet and boom vang are given as well.

In case of big sailing yachts previous methods may not apply. It becomes therefore suitable to perform a more accurate investigation on mast and rigging stresses by finite element programs which allow the simulation of the structural behaviour in a more realistic way, taking into account the three dimensional nature of rigging geometry and load distribution. Furthermore it is possible to study a number of numerical models corresponding to the sail plans of practical interest under different loading conditions. Using such refined approaches, the final scantlings of the mast can be lighter as compared with those obtained using empirical methods.

Both linear and non linear approaches are allowed by FEM technique. A linear analysis starts from a set of previously defined loading conditions chosen by the designer on the base of the boat type, cruising or racing. An example of a linear approach to the mast scantling by FEM technique has been presented in Boote, 1990 consists in applying the loads achieved by Skene's method and verified by other sources, to a linear FEM model of rigging.

The stiffness of stays and shrouds is simulated modifying the steel Young Modulus with a reduction factor provided by the constructor. The resulting "apparent Young Modulus" depends on the rope winding and the security factor at which the rope operates; in general it can be assumed equal to one/half of the steel Young Modulus for 1x19 wire. In order to partially overcome the non-linear behaviour of wires, it is necessary t to eliminate the elements in which a compressive load is expected. In case the structure is complex and some doubt exists on the stress distribution, by a first calculation on the complete model, the compressed wire elements will be individuated and removed. In the successive phase the second, final calculation is run with same loads.

A complete distribution of bending and compression along the mast is then obtained. The results are assessed in terms of stress and displacements. As regards buckling the verification is performed by calculating the Eulerian buckling loads for each panel with the corresponding end conditions and to compare them with those achieved by FEM analyses. A more rigorous approach consists in considering the combination of compression and bending on each unsupported panel and evaluating them by the interaction curves N-M method (see Mazzolani, 1974).

Many other works are available on this approach. Among the most recent ones, Grasse (2003) presented a linear FEM analysis of a 10m research sailing yacht which has been instrumented to gather experimental data. Janssen (2004) presented a mast design tool, called BESTMAST, which predicts sail forces in different sailing situations and applies them to a finite element model of the rig. During the analysis the rig can be optimised. Pallu et.al. (2008) carried out an integrated software tool, called SIMSPAR, dedicated to mast design and tuning. The software is based on a linear finite element approach and it provides a set of typical sail critical loads (closed hauled, broach under spinnaker and running under spinnaker). The software also performs buckling analysis of the mast tube and a comparison with NASTRAN software is presented as well. Miller and Dillon (1994) explored dynamic structural effects of the sail-mast interaction, including damping effects of the composite mast. Shenoi et.al. (2006) showed an effective approach at mast optimisation using statistical experimental approaches combined with FEA analyses.

As a matter of fact the mast and the rigging have a typical non-linear behaviour due to the very large displacements of mast (geometric non-linearities), the uni-lateral behaviour of wires and the non-linear stress-strain curve of both mast and wire material. To take into account such non linearities, the shrouds contribution and the correct distribution of the compressive load a rigorous structural analysis by a non-linear finite element program is mandatory. To consider the large displacements of fractional rigs a 3D geometrically non-linear program using the matrix stiffness method was developed by Coakley (1989) based on an earlier linear program developed by Hoste (1978). A non-linear finite element analysis of a complex mast is reported in Boote and Caponnetto (1991) in which the authors developed a non linear code, specifically for mast analysis. Further developments of inhouse codes include interactive software developed by some leading sailmaking companies. One example is the North Sails MemBrain and FLOW codes. FLOW is a CFD panel-based code that determines the sails' loads, which are fed to MemBrain for rig analysis (Richter and Braun, 2003). MemBrain takes the loads and using linear beam elements analyzes rig deformations, with an additional step determining whether rigging goes slack. An iterative loop between FLOW and MemBrain converges the sail shape and rig deformations.

Nowadays, a large number of multi-purpose non linear FEM codes are available; nevertheless their cost remain too high for a private designer and their use is still complex and addressed to long-experienced specialists. On the other hand the more complex element library of non-linear FEM softwares allow to model the rigging in a more realistic way. For mast and spreaders non linear thin walled beam elements can be used, which take into account stress stiffening, large deflection and shear deflection; they have plastic, creep and swelling capabilities as well. Whatever geometry of the section, open or close, can be simulated; this is particularly useful to schematise complex mast sections like in case mainsail reefing systems are fitted. Non bilateral rod elements can be used for wires; this kind of rod has a bilinear stiffness matrix that allows to schematise tension-only elements with initial strain. This last feature is particularly interesting to simulate the pretensioning of the rigging.

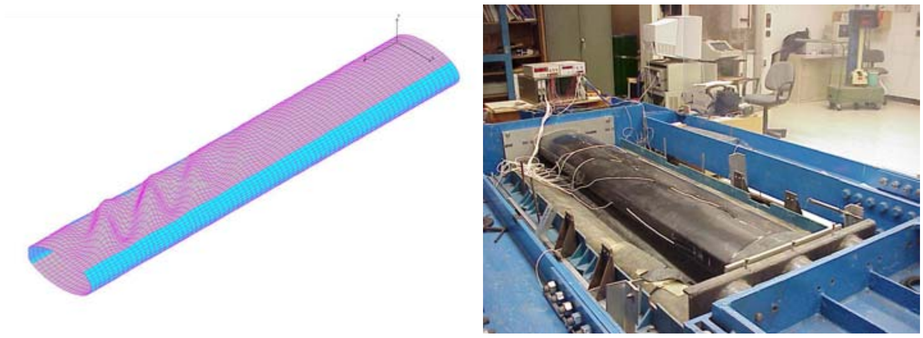


Figure 17: Numerical-experimental analyses of a composite mast section: (a) numerical buckling mode; (b) test set up on a mast specimen (Miller, 2003).

A challenge with all masts, with particular reference to carbon/epoxy masts, is determining the actual buckling capacity in comparison to the idealized Euler buckling predicted with finite elements. Manufacturing issues such as residual extrusion stresses in aluminium or uneven curing stresses in epoxy or asymmetric laminates reduce the actual buckling capacity. Tests on America's Cup masts compared to nonlinear finite element results using laminated shell elements (see Figure 17) showed capacities reduced by 30% (Miller, 2003). To more accurately account for uncertainties in loads and construction a reliability approach as opposed to a traditional factor of safety was recommended for masts (Miller, 1995).

4.5 Rules and Design Standards

Few dedicated Rules exist for sailing yacht rigs A specific section was contained in the old version of Det Norske Veritas Rules for construction and certification of vessels less than 15 metres (DNV, 1983). A similar section is presented in 1993 Bureau Veritas Rules for the classification of yachts (BV, 1993). Both of them presented a quite complete set of formulas to calculate the minimum cross section inertia of mast panels. Unstayed and stayed mast up to two orders of spreaders are considered together with other components like spreaders, booms and running riggings. Some additional information are contained in the new version of DNV Rules for vessels less than 15 metres (NBS, 1990. In the new BV Rules (BV, 2006) the rigging loads are considered as global loads inducing vertical bending moments on the hull girder; only loads on chainplates are provided.

The Germanischer Lloyds facesd the problem in depth by a dedicated series of rules for tall ship rigs (GL, 1997), large modern yacht rigs (GL, 2002) and carbon strand and PBO cable rigging (GL, 2008). While GL (1997) refers to old style sailing ships with traditional rigs, GL (2002) contains a full set of rules to calculate sail forces distribution on modern yacht standing rigging. Design formulas for shrouds, spreaders and wang are provided as well.

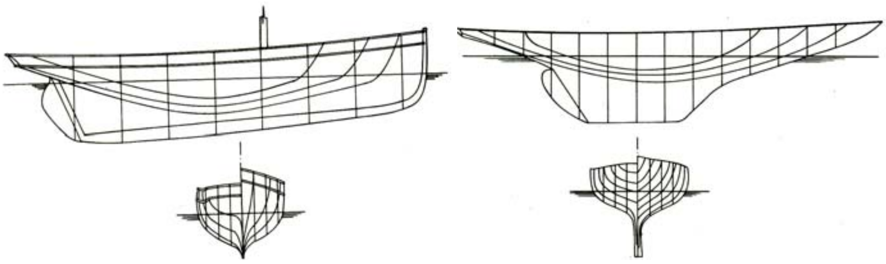
Further the developing ISO Standards contain some paragraphs about rigging loads (ISO, 2005) though, at this moment, the rules seem to be not yet in their definitive version.

5. APPENDAGES

5.1 Arrangements:

As far as the arrangements of the appendages, i.e. keel and rudder, are concerned a considerable development has taken place over the past fifty years or so.

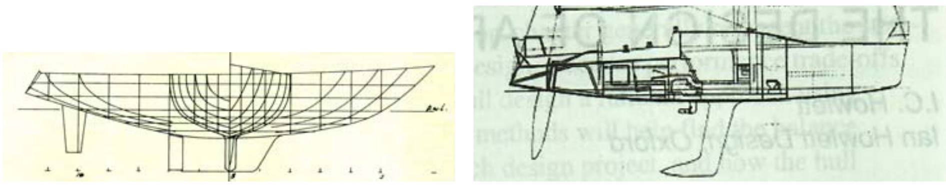
At first in the wooden construction period the long and integrated keels with the rudder hung at the aft end were the fashion. The layout was partially dictated by the possibilities and restrictions imposed by the available materials and methods of construction at that time. The ballast weight was connected to the fore ward bottom part of the keel and usually constructed of lead or cast iron. The keel was an integral part of the hull and thus faired in the hull over a considerable part and was more or less a peaked vertical extension of the hull. A trend that came from the older designs which started to use more and more V shaped sections in the hull to generate side force so it was in a way a further development of the hull shape evolution at that time. The keel was not considered as a wing. The rudder was more or less a flap at the aft end of the keel and owed a large part of its effectiveness from a considerable force (lift) carry over on the keel just in front of it. After the transition to steel hulls the shape remained the same for a considerable period of time – see Figure 18.



Yacht from late 1800’s Yacht from 1930’s

Figure 18: Yacht keel forms from yesteryears

After the Second World War the keel and the rudder became more and more separated. Both keel and rudder were treated as lift generating wings and so the plan form and section shape considerations based on wing theory came into play. The keel became more and more an isolated wing, with less and less fairing in the hull. At the beginning of relatively low aspect ratio, i.e. long chord and relatively short span. Later, pushed forward by effectiveness considerations, the aspect ratio increased. At present usually only restricted by draft and constructional considerations. In the quest for efficiency all kinds of keel planforms did see the light each with its own structural challenge. Just to name a few: the elliptical keel, the upside down keel, the high sweep angle keel and the “Mickey Mouse” keel. Modern forms are shown in Figure 19 below.



Yacht from 1950’s with separated keel and rudder Yacht from 2000’s with high aspect keel + bulb

Figure 19: Modern yacht keel forms

At the same time however the keel is also used as the ballast container and so, depending on the specific weight of the material used, the volume and the vertical centre of gravity of the keel are important design considerations also. Less draft means more weight to achieve the same stability. To lower the centre of gravity of the ballast as much as possible the application of a bulb placed at the bottom end of the keel came over the horizon. At first just as a thickened lower section of the keel was used, later becoming more and more a bulb shaped extension at the lower end exceeding the chord length at the tip. At present extreme bulbs exceeding in length many times the length of the chord at the tip extend at the bottom of the keels containing considerable amount of weight at the extreme lower end of the fin.

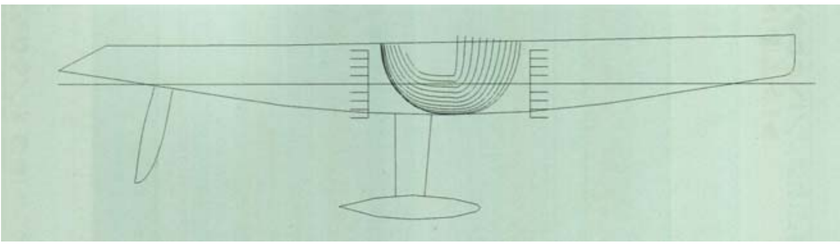


Figure 20: High tech yacht with high aspect ratio keel, heavy bulb and very slender rudder

The rudder in this separated twin foil concept is placed in full isolation of the keel usually at the end of the waterline; see Figure 20. The distance between keel and rudder has increased continuously over the years, leaving the rudder also more and more exposed. Increasing the gap is considered beneficial from a minimum interference point of view, but also arose due to the fact, that both foils increased in aspect ratio effectuated mostly by reducing chord length.

In a limited number of cases a transom hung rudder was (is) used. Most of the time this type of rudder is used when the hull is truncated at the waterline end anyway. This is done for various reasons, i.e. giving the possibility for easy removal with trailer sailors or drying out, weight saving in the ships end, the accessibility for damage control or the design rule used.

Several other appendage arrangements have been used over longer periods of time for ships with a restricted draft requirement:

- One solution is the application of a centre board extending from a slot in the keel. When the centre board rotated out of the keel it was usually a high aspect ratio fin, which rotated in the shelter of a low aspect ratio keel.
- Or a quarter circular plan form was used, which allowed the keel to be shorter (but with larger span) but which was, at its own, less effective.

In all these cases however it was more difficult to apply a bulb and the bulb became less effective. At the same time due to the shallow draft a low centre of gravity of the (short span) keel was asked for to save as much weight as possible. Also the keel sections became quite fat, just to be able to house the centre board.

- So another solution was found in the lifting keel. In this concept the entire keel is lifted in a case inside the hull. This is achieved just for a part of the keel span enough to reduce the draft to the desired limit. When raising the keel however the ballast is raised also asking for particular attention with respect to the stability. Also from a constructional point of view, the restriction of the freedom and fixation of the keel when either raised or (partly!) lowered is a point of considerable concern. The lifting keel inevitably has a constant chord, a vertical leading and trailing edge and a constant section shape over the range of the span over which the keel is lifted in the casing.

- Various other solutions have been used also of which, from a constructional point of view, the twin bilge keel concept should be mentioned. Here two smaller keels are applied at the "chine" of the hull, one at either side. This concept combines the advantages op both shallow draft and easy drying out. Its use however is generally restricted to smaller craft employed in reputed drying areas mainly in estuaries of the UK and France.
- Finally the keel with winglets at the tip should be mentioned as a possible limited draft solution.

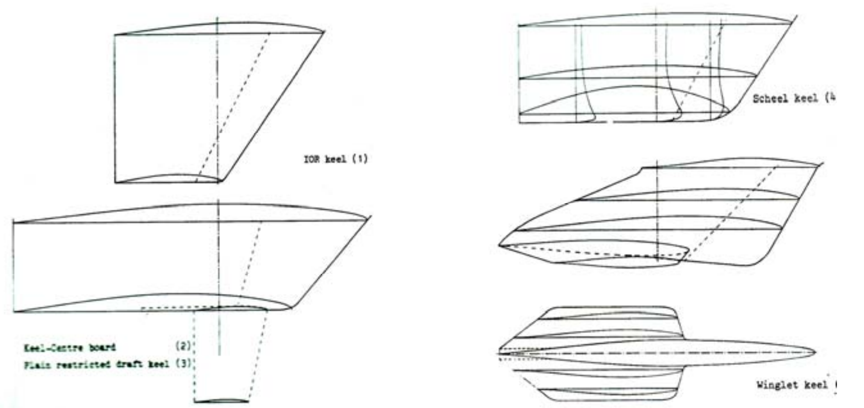


Figure 21: Typical plan forms: IOR keel, Shallow draft with centreboard, Sheel keel and Upside down keel with winglets

Typical plan forms are shown in Figure 21. A rather new development is the canting keel arrangement, in which a very high aspect ratio keel fin fitted with a high weight bulb at the tip is canting to weather. The intent is to raise stability of the ship, by moving the keel to weather when sailing on one tack, without increasing the displacement of the boat through the use of movable ballast in water tanks. The whole mechanism to cant the keel is of considerable structural concern, with a number of failures noted in the early development years. As the operation of the keel when under way in demanding conditions is more similar to that of a racing dinghy than a traditional keel yacht, so at present its application is restricted to boats with highly experienced crews. Due to the fact that the keel may cant over something like 60° the loss of efficiency in generating hydrodynamic side force to counteract the forces on the sails has to be overcome by the use of dagger boards, usually just forward of the mast.

New developments in rudder layouts may be found in the application of twin rudders. They are typically applied on boats with beamy aft sections. These boats would lift the centreline rudder out of the water to a considerable extent when heeled. The twin rudder arrangement yields more control when heeled because in those conditions always one rudder always remains fully submerged and almost vertical. Also when running downwind the twin rudders supply the necessary directional control. A disadvantage is found in the fact that these twin rudders are placed off centre and therefore are no longer protected against collision with debris etcetera by the keel placed in front of them, the advantage being that the chance of damaging them both at the same time is small.

5.2 Material Selection Criteria

In general it should be mentioned that any rule, if applicable, does not allow the use of materials for ballast with a higher specific weight density then lead. So in a way the choice is limited.

When the keel was an integral part of the hull the material of choice was the same as for the hull, i.e. wood and only the ballast part of the keel was fabricated from either lead or cast iron.

In the transition from wood to newer hull construction materials for yachts, such as steel, aluminium alloy and (glass) fibre reinforced polyester, also new construction material for the appendages were used. In steel and aluminium alloy hulls the keels were often made also of the same material as the hull and the ballast was poured in from the outside after finishing of the hull. This implied that usually lead was used. In more modern hulls from these metals still the keels are made from the same materials, welded to and being integral part of the hull. Even when the keel is not faired into the hull over a considerable of its length as with the wooden hulls

The choice of materials for the keels, both when the keel is a separate appendage and when it is structurally independent, is influenced by a number of considerations: i.e.:

- the structural requirements of the separate fin,
- its connection to the hull,
- the specific weight density of the materials used
- the cost involved.

Two materials dominate the field:

- Lead. Lead has the higher specific weight density of the materials allowed. It comes close to 11 tons per cubic meter depending on its purity, but is quite expensive. In particular because some 4% of its weight has to be added as antimony to the pure lead to give it more strength. Typical application of this choice is in the more performance orientated designs. also the health and environmental precautions, which have to be taken during melting and pouring, contribute to the cost.

- Cast iron. Cast iron has a specific weight density of around 7.8 tons per cubic meter but is structurally sound on its own. It is much cheaper, both in acquisition and in manufacturing. Also casting is much more common practice and less of a hazard. Typical application of the cast iron keel is therefore in the cheaper series production boat market though it often leads to corrosion problems.

For the really high tech sailing yachts, constructing the keel from one material throughout is not strictly necessary. The fin is considered to be the wing producing side force and holding the ballast weight down. So in these very high performance and/or racing boats the fins and the ballast are separated and the keel fins are entirely made of carbon fibre. The bulb is then still made of lead and is connected to the lower end of the fin to maximize its effect on the stability of the yacht, while having also the maximum weight available in the bulb, because no weight is "wasted" in the fin. Some (racing) rules however do not allow this application anymore.

In some special applications, such as for instance IACC yachts, also forced steel fins of very high quality steel alloys are being used. But also "cheaper" solutions such as the use of bronze for the fin construction materials are known. Lead still being the favoured material for the bulbs.

When dagger boards are being used in combination with canting keels almost all of them are manufactured from carbon fibre reinforced resins.

The rudders are originally made of wood just like the hulls. The rudder stock was from steel or bronze. With steel and aluminium alloy hulls the rudder blades and the rudder stocks are constructed from these metals also.

In the situation of GRP hulls the rudder blades were constructed from GRP also and depending on the emphasis on performance in the design under consideration the rudder stock was from stainless steel of aluminium alloy. Originally the two sides of the blades were made separately and the rudder stock glassed to one side before the two sides were joined together. Later high density foam cores were used to shape the blades and the rudder stock laminated in before hand. Sometimes wood cores were used also.

For high performance applications nowadays complete carbon fibre rudder blades with integrated full carbon rudder stock are made in one piece.

The main considerations for the material choice for the rudder are:

- weight,
- strength and
- stiffness.

In the case of a rudder in particular the weight is considered important, because the reduction of the longitudinal radius of gyration of the yacht is considered to be of great importance for reducing the added resistance of the yacht sailing in waves. Strength and stiffness are obvious requirements. Stiffness is essential because with free hung rudders deflection of the rudder stock leads to the rudder getting stuck in the bearings.

5.3 Connections and attachments.

The connection of the keel to the hull is very dependent on the type of yacht under consideration although some elements remain.

With the traditional long keel under the wooden hull a clear distinction between hull and keel is not easy to make. The hull construction consisted of a long wooden stem, connected to the keel beam which on his turn ends in the stem beam. Frames, beams, transverse girders and stringers were used to supplement the construction of the hull planking. The ballast is separated from the hull by means of a piece of wood, called dead wood. The keel bolts run trough the deadwood and through the beams to take the transverse load and moment under sail. Grounding loads are more difficult to handle with this construction.

The rudder in these wooden long keel yachts is connected to the keel by means of hinges and the rudder stock has a through hull and trough deck bearings at the top and is supported at the bottom by an additional bearing on the keel balk. Figures 22 and 23 show examples of wooden and mixed metallic constructions.

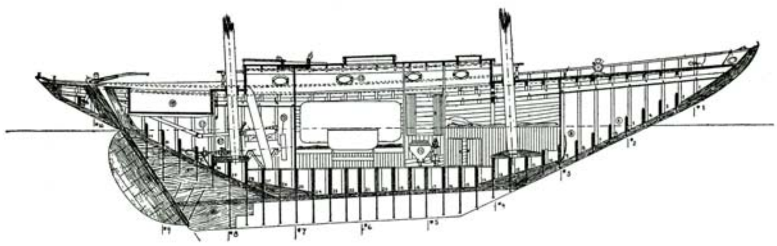


Figure 22: Typical wood construction of 1930's type yacht

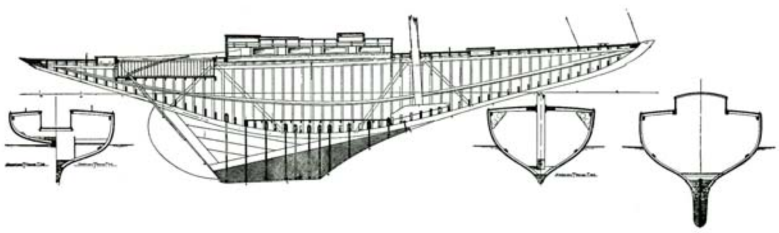


Figure 23: Mixed construction of steel frames , knees, floors etc and wooden hull and deck

Also with some elderly shaped yachts constructed in steel, aluminium alloy and GRP the integral keel is a often deployed hull shape. The keel is now integral part of the hull (S shaped hull) and the usual internal stiffeners are used to take the loading from the keel into the hull structure. The ballast is poured later into a void in the keel.

In the separate keel design the keel in the metal hull construction is welded to the hull and forms also an integral part with the hull construction with the frames and the floors extending in the keel. In some designs a separate keel of lead and cast iron is bolted to the hull with a similar construction as used with the hulls constructed in GRP

In GRP hulls, with a separate keel attached to the hull, the construction is generally similar to the construction used in wood, i.e. hull plating stiffened with floors, transverse beams and longitudinal girders. There is however one noticeable and important exception, i.e. the keel bolts run through the hull but not through any of the floors or the transverse beams. They are drilled through only the hull in between or just adjacent to the floors or transverse beams. This less favourable construction technique is initiated by the fact that none of the floors or any of the transverse beams in the GRP construction are solid beams, as in the traditional wood construction, but they are made from GRP laid just over a core, usually high density foam or wood of much lower density. These stiffeners simply, by the very nature of their construction, can simply not take the high compression loads associated with the keel bolts passing through them. The keel bolts are put through the hull laminate and backed at the inside by steel plates of hopefully sufficient large size. The fairing of the edges of these backing plates is essential to prevent damage to the laminate of the hull with sometimes catastrophic results.

With series production boats this construction technique poses another serious challenge for the builder because in those boats often internal moulds are being used, containing all the internal stiffeners used for engine support frame, the floors, the mast foot support, the shroud plates and the transverse and longitudinal stiffeners in the keel connection area. This is placed as one piece in the hull. However solid this construction may seem the quality of the (secondary) bonding between the internal mould and the hull laminate is essential for the final strength of the construction. The absolute exact positioning of the internal mould with respect to the hull and the precise shape of both is crucial to prevent voids in between, which are marginally filled during bonding by resin only. The bonding material consists usually of thickened resin (putty) only and no fibres to yield any strength at all. The shortcomings of this kind of structure have become quite evident in real life after such structures have been exposed to grounding loads or extreme slamming loads.

In some constructions this internal frame is made of metal, i.e. steel or aluminium, taking all the principal loads. The frame has sufficient strength and stiffness of its own and is laminated to the hull after hull laminate completion. This is generally considered to be a much more reliable and functional construction but also more expensive. Concerns include long-term corrosion resistance.

The new trend to ever shorter keel sections at the top combined with reduced section thickness leads to severely reduced section width available to place the keel bolts transverse apart sufficiently to take the transverse moment exerted by the keel under heel within reasonable limits of the forces involved. Also the transfer of all the (extreme) keel loads, both longitudinal, vertical and transverse, to the hull has to be taken care of by a seriously reduced hull area. All this makes that particular part of the hull to a very highly loaded area.

To overcome this problem in cast iron keels (production boats) often a much wider and longer flange at the top of the keel is fabricated to which the keel bolts are connected, spreading them over an area outside the actual keel section itself. This flange is then placed in a prefabricated recess in the bottom of the hull.

With high performance keels this additional weight involved with the application of such a flange at the top of the keel is considered to be non beneficial from a stability and weight point of view and so for the optimal performance of the yacht. So the solution is sought in another direction. Here the fin of the keel is extended inside the hull by means of some kind of keel casing. This casing is made as a solid structural part fully integrated with the hull structure. It supports the keel now both at the through hull intersection and at the cabin floor height, and so taking the longitudinal and transverse moments in a more adequate way. While castings are common, forged steel provides higher performance.

For the rudder attachment various constructions are used, very much depending on the type of rudder used:

- The long keel with the rudder hung to the aft end of the keel, the construction sometimes uses hinges on the keel and certainly a bearing of the rudder stock in the bottom part on the keel and in the through hull position, complemented with a bearing at deck level.

In the separate foils configuration, i.e. with the free rudder several possibilities occur:

- The rudder has a fixed skeg in front of it over the entire span of the rudder. The rudder stock is supported in the through hull opening and at the bottom of the skeg, usually complemented with a bearing at deck level or at the cabin sole height. The three support system of the rudder stock makes it possible to reduce the rudder stock diameter and so its weight. It should be emphasized however that this assumption is only valid when the supporting skeg in stiffness seriously exceeds the stiffness of the rudder; otherwise the rudder stock supports the skeg instead of vice versa. In the practice of boat building this is often difficult to achieve, in particular in GRP construction, due to the fact that the skeg is difficult to access during construction.
- The rudder has a fixed skeg in front of it but only over a fraction of the span. In principal the same construction technique is applied as mentioned above. The gain in rudder stock diameter is smaller, but there is a gain in

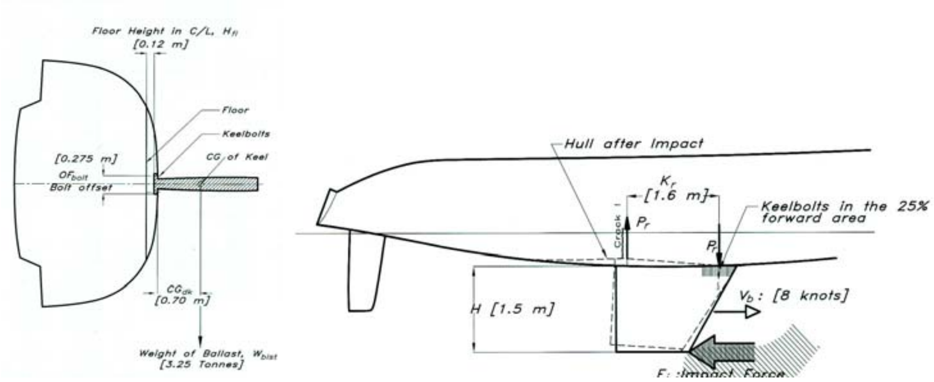
hydrodynamic efficiency with these rudders.

- The free hung spade rudder. This is the most commonly used rudder nowadays. The rudder stock is only supported by two bearings: one in the through hull point and one somewhere higher up, usually at deck level or at the cabin sole. This construction leads to considerable rudder stock diameters to account for the large bending moment. Great care has to be taken to make the construction at the location of the bearings very stiff and with sufficient strength, in particular at the lower bearing.

5.4 Loadings and Load assessments.

The most important loadings on the keel and its supporting structure inside the hull are (ranked with increasing importance) :

- Side force and associated moment under sailing conditions in combination with ship motions in waves
- Forces and moments during a 90° knock down
- Forces and moments due to grounding at speed



90° of heel load case for keel Grounding load case for keel

Figure 24: Loadings on keels

The typical loadings associated with the two first load cases (see Figure 24) may be derived from

- A extensive Velocity Prediction analysis combined with
- A ship motions in waves analysis for the particular yacht under consideration

These load cases are primarily used to gain insight in the possible fatigue aspects involved with the material selection and the construction chosen.

The second load case is used to dimension the transverse strength requirements of the hull construction in the keel connection area as well as for, if applicable, the required dimension of the keel bolts. In general only the static loads during the knock down are considered and no dynamic effect is taken into account.

The last load case is particularly important as an extreme load case. The yacht is considered to run aground with a specific forward speed at the keel tip. All kinds of variables come into play, which are difficult to determine, such as:

- At what speed does the grounding take place? Actually any speed can occur, from hull speed up to planning speeds. It is obvious that the selection of which speed to use has an significant effect on the outcome.
- Which are the soil mechanical properties at the point of impact and of which material is the keel made? These two determine to a large extend the character of the collision, i.e. anything in between fully elastic (any keel in low density mud) to fully non elastic (cast iron keel against a full rock)
- What is the deceleration rate after the collision?

The answers to these questions are often very difficult to give and so in the design load calculations many assumptions are being made. In general the ruling specifies a deceleration rate due to the grounding phenomena, which determines the load on the keel (and the yacht). Most designers also use their own assessment method, which they have validated against their own experience. This usually works out, although the lack of sufficient experience with the more modern and more extreme keel layouts has lead to a series of recent severe accidents with serious results.

For the new generation of high aspect ratio fins combined with a heavy bulb at the tip which exceeds in length the chord length many times, additional load case come into play. Apart from the bending moment also a considerable torque moment may arise depending on the exact position of the bulb centre of gravity with respect to the fin. In a dynamic situation (waves) natural frequencies become important in this respect, in particular with regard to the possible occurrence of flutter.

For the assessment of the design load on the rudders a similar situation exists. Here the main parameters involved are:

- What is the maximum speed of the yacht? Under what condition is the maximum rudder force required? Usually a percentage of the yacht hull speed is taken (generally much larger then 100% !)
- What is the maximum achievable lift coefficient under those conditions? Is the maximum lift considered to occur under attached flow with maximum lift or during stall? This yields different positions of the centre of effort: in the first case around 25% of the chord and in the second condition around 50%. One of the actual limitations is often found in the physical strength of the helmsman or mechanical properties of the steering gear, they must be able to apply the steering moment on the helm also!
- So also the balance of the rudder comes into play. Too much balance may lead to an increase of possible side force on the rudder. The balance or the lack thereof also introduces a considerable torque moment on the rudder stock.

Some designers actually consider the condition that may be encountered by the yacht during a severe storm, in which the yacht might be pushed astern with great force and the rudder swinging out of control and jammed against it stops, as the highest load condition. And indeed a lot of rudders have been lost under those conditions.

5.5 Appendage structural response and methods

Structural analysis for appendages has followed a similar process development to hulls and rigs with specific concerns needed for particular loading. Classification Society procedures largely follow a linear beam analysis with the assumption of isotropic material properties. Appendages are usually treated as cantilever beams. Torsion plays a significant part in the load resolution however and combined stress equation is used to determine the equivalent total stress.

As described in the load section the primary forces are hydrodynamic and grounding. Depending on the angle of attack the pressure centre for the hydrodynamic loads varies and the conservative assumption is that the maximum lift is located at 50 % of the chord during a stall. This procedure produces the greatest torque although an argument could be made that when going astern the centre of pressure could be further away from the stock. Another assumption commonly taken is that the span position of the maximum lift is at the geometric centroid. This assumption relies on the hull not providing an end plate effect and the result is a conservative bending moment.

Other than hydrodynamic loading the principal loadings are from grounding and collisions with flotsam. The two can be treated similarly in that they can be resolved in a bending moment and a shear force. Although inherently dynamic, a quasi static approach is usually taken for simplicity. As the time to decelerate is dependent on the structural geometry and the bottom conditions, as explained before, the deceleration interval is highly variable. ABS for instance used 0.25 sec in their guide. The typical grounding force is applied in the vessel longitudinal direction. Whether this is correctly addressed the common situation of a vessel broaching while grounding in waves has not been determined.

Simple beam theory has proven generally reliable due to the conservative nature of the load prediction and the isotropic characteristics of common lead and steel keels. Problems however been seen in welds of fabricated steel keels and in keel connections to composite hulls shells. Both can be traced to fatigue issues as the problems occur after years in service. Knock down factors are applied to the material properties, which given the large number of wave loading cycles leads to the use of materials endurance limit value. This can be easily under estimated for materials such as polyester/E glass where the endurance limit, if one exists, may be less then 20% of the initial strength

For composite appendages a combination of linear beam theory and laminated plate theory is used. For high performance applications in any material finite element analysis is used, with one example of a detailed study involving tank testing correlation to FEA showing good results (Miller 2000)

High aspect appendages are subject to aeroelastic flutter if not sufficiently torsionally rigid. Fluid structure interaction plays a part with the water providing significant damping at low frequencies.

6. CONCLUSIONS

The scientific, engineering and technical bases of yacht structural design are evolving in sophistication with lessons from many advances achieved in this sphere, particularly at the high-end racing yacht design, being drawn in in other marine applications. It is also clear that there remain several challenges for designers and researchers.
Some of the principal areas for further scientifically-based research include:

- Determination of hull girder loadings
- Clarification of keel and rudder load contributions and interaction with hull girder
- Sail and rig-derived loads on the hull
- Structural response analysis of the hull girder
- Effective methods for assessment of masts and rigging responses
- Development of structural topologies involving new material combinations for improved toughness

Areas identified by industrialists through their feedback via the questionnaire are listed in Table 5.

Table 1
Business details and materials usage amongst industrial organizations

Business type	Designer	Designer Consultant	Designer	Designer	Class. Soc.	Designer Consultant	Designer	Spar + rigging mfr
No. of employees	<10	<10	<10	<10	>100	50-100	<10	50-100
No. of boats	@7	@3	@5	Varied	@7	Varied	10-20	Varied
Type of boats	Cruising yachts Series prodn.	Racing yachts Cruising yachts Mega yachts Series prodn.	Racing yachts Cruising yachts Series prodn. Dinghies	Racing yachts Cruising yachts Mega yachts Masts	Racing yachts Cruising yachts Mega yachts Series prodn.	Cruising yachts Mega yachts Series prodn.	Cruising yachts Mega yachts Series prodn.	Rig units for: Racing yachts Cruising yachts Mega yachts Series prodn. Dinghies
Materials specified – FRP reinforcements	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid
Materials specified – FRP resins	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy
Materials specified – FRP cores	EG Balsa Plywood PVC Foam Honeycomb	EG Balsa Plywood PVC Foam Honeycomb	EG Balsa PVC Foam Honeycomb	EG Balsa PVC Foam PU Foam Syntactic foam Honeycomb	EG Balsa PVC Foam PU Foam Honeycomb	EG Balsa PVC Foam PU Foam	EG Balsa PVC Foam Honeycomb	PVC Foam PU Foam Honeycomb
Materials specified – non-FRP	Wood Aluminium	Wood Steel Aluminium	Wood Aluminium	Wood Steel Aluminium	Wood Steel Aluminium	Steel Aluminium	Wood Steel Aluminium	Steel Aluminium

Table 1 (contd)
Business details and materials usage amongst industrial organisations

Business type	Boatbuilder Consultant	Designer Consultant	Designer Consultant	Boatbuilder	Boatbuilder Moulder Designer	Designer	Designer	Designer
No. of employees	>100	<10	<10	50-100	>100	<10	<10	<10
No. of boats	2-10	Varied	5-10	30	>100	1-2 New 3-10 Refit	Varied	Varied
Type of boats	Racing yachts Others	Racing yachts Cruising yachts Mega yachts Masts	Racing yachts Mega yachts Series prodn. Rowing shells	Cruising yachts	Racing yachts Cruising yachts Series prodn	Racing yachts Cruising yachts Mega yachts Series prodn. Masts	Racing yachts Cruising yachts Series prodn.	Racing yachts Cruising yachts Mega yachts Series prodn. Dinghies
Materials specified – FRP reinforcements	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar	Glass Carbon Hybrid	Glass Carbon Kevlar Hybrid	Glass Carbon Kevlar	Glass Carbon Kevlar Hybrid
Materials specified – FRP resins	Epoxy Vinyl ester Phenolics	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester Phenolics	Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester	Epoxy Polyester Vinyl ester
Materials specified – FRP cores	PVC Foam PU Foam Honeycomb	EG Balsa PVC Foam PU Foam Plywood Honeycomb	EG Balsa PVC Foam PU Foam	Plywood	EG Balsa PVC Foam PU Foam	EG Balsa PVC Foam Honeycomb	PVC Foam Honeycomb	PVC Foam Plywood Honeycomb
Materials specified – non-FRP	Aluminium		Aluminium	Wood	Wood Aluminium	Wood Aluminium Steel	Aluminium	

Table 2
Design models and production methods used by industrial organisations

Business type	Designer	Designer Consultant	Designer	Designer	Class. Soc.	Designer Consultant	Designer	Spar + rigging mfr	Boatbuilder Consultant
Design codes	RCD/ISO ABS DNV	RCD/ISO ABS DNV GL	ABS DNV NK	RCD/ISO BV DNV GL	ABS Mil ASTM MCA IMO USCG ICLL	RCD/ISO BV DNV GL LR RINA	RCD/ISO ABS DNV GL LR MCA	GL	ABS ABYC
Software	Naval arch.	Naval arch. Rhino Autocad	Naval arch. Rhino	FEA (Nastran, Nisa) Resistance Sail load	FEA	FEA (Stand 7) Autoship Autohydro Resistance Seakeeping Rhino Ship constructor	Naval arch. Solid works Autocad Catia	FEA Autocad Solidworks	FEA (Cosmos) Pro Surf Rhino Solidworks
Production methods - metals	Welding	Welding	Welding	Welding Bonding	Welding Bonding Mech fastening	Welding Bonding	Welding	Welding Bonding Riveting	Welding
Production methods – FRP	HLU Spray VARIM Pre-preg Bonding	HLU VARIM Pre-preg Bonding	HLU Pre-preg	HLU Spray VARIM RTM Pre-preg Bonding	HLU Spray VARIM RTM Pre-preg Bonding	HLU Spray VARIM RTM Pre-preg Bonding	HLU VARIM Pre-preg Bonding	HLU Pre-preg Bonding	HLU VARIM Pre-preg
Production methods - wood	Traditional Cold mould	Traditional Cold mould Bonding	Cold mould Bonding	Traditional Cold mould Bonding	Traditional Cold mould Bonding		Cold mould Bonding		Cold mould

Table 2 (contd.)
Design models and production methods used by industrial organisations

Business type	Designer Consultant	Designer Consultant	Boatbuilder	Boatbuilder Moulder Designer	Designer		
Design codes	ABS GL	ABS LR ABYC	RCD/ISO LR	RCD/ISO ABYC	RCD/ISO ABYC	RCD/ISO ABS DNV	ABS GL LR RINA MCA ISO DIN ASTM
Software	FEA	CFD (Splash, XFOIL, Comet) Macsurf	Naval arch Product modelling	Naval arch Product modelling	FEA CFD (FlowSim) Multisurf Wolfson Unit Hydrocomp GHS	FEA CFD Naval arch Product modelling	FEA CFD Naval arch Product modelling
Production methods - metals		Welding Bonding	Welding	Welding Bonding	Welding	Welding	Welding
Production methods – FRP	HLU Spray VARIM Pre-preg Bonding	VARIM Pre-preg Bonding	HLU Spray VARIM Bonding	HLU Spray VARIM Pre-preg Bonding	HLU (repair) VARIM Pre-preg Bonding	VARIM Pre-preg Bonding	VARIM RTM Pre-preg
Production methods - wood				Traditional Cold mould Bonding	Traditional Cold mould Bonding		Cold mould

Table 3
Industrialists perspective of challenges for the future

Business	Challenge
Designer	Design • High modulus carbon / epoxy materials characterization with manufacturers process • Carrying out campaigns testing to verify and characterize the efforts due to wind and the sea (slamming, impact) • Train engineers and designers for technical calculation of composites
Class.Soc.	Design • Understanding material behaviour in conjunction with structural application Production • Production exceeding design resulting in late 'fixes' in the vessel being built Rules and regulations • Conformity amongst class. Societies and government agencies in regard to safety codes
Designer Consultant	Rules and regulations • Large yachts over 3000GRT and over 12 passengers
Spar + rigging mfr	Rules and regulations • Fitting GL or similar requirements to rigging
Boatbuilder Consultant	Design • Translating 3D modelling capabilities to the shop floor in a meaningful form Rules and regulations • Varied interpretations (of subjective nature) of EPA/OSHA rules
Designer Consultan	Design • Comprehensive methods for developing loads, both working and ultimate for structural design which is consistent in the industry for various classes of yachts – and consistent usages of tested composite material data, and the connection between loads – margins – and material data. • A consistent industry wide approach for analysis of secondary bonding and taping.

Designer Consultan	<u>Design</u> • Sail force prediction models; performance prediction for light weight planning hulls and how to handicap against displacement hulls. <u>Production</u> • Better mould material for elevated temperature curing of pre-preg. • Better techniques for one-off prototyping. <u>Rules and regulations</u> • Lack of structural standards; lack of uniform racing rules <u>Environmental issues</u> • Hull damage due collisions with debris in ocean • Boat yards have many environmental problems
Boatbuilder	<u>Production</u> • Shortage of teak <u>Environmental issues</u> • Increased stringency forecast
Designer	<u>Design</u> • Lack of official bodies to offer interpretations to the rules/guidelines. Leaves ambiguity in certain cases.
Designer	<u>Production</u> • Production techniques have tended to drive the bottom of the market, leaving the middle and higher end of the market to too much hand labour, driving up the price point for quality disproportionately <u>Rules and regulations</u> • The regulating authorities tend to have not been intended for use with sailing craft, and rules such as MCA conflict directly with the intent and use of the craft, and at times take away from sea keeping. <u>Environmental issues</u> • The biggest issue. Both for resources used, and recyclable. Energy use, type, and supply is going to be a critical issue that defines the future of the industry.

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