Structural design and loads on large yachts

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The design of a yacht, in the broad sense, involves the entire process from the initial design concept to the final approved design ready for fabrication/manufacture. An important part of this process is the design control, or structural analysis stage, to ensure reliability against structural failure. Design control, therefore, consists of a number of steps:
• evaluation of environmental conditions,
• analysis of loads,
• analysis of response,
• evaluation of strength, and
• control of safety.

The analysis methods used may be based on theory, experience, or on experiments. Full scale measurements could be used, when a (near) sister vessel is available, or when there reliable methods to correlate the results to the design at hand are available.

Conventional mono-hull steel ship structural design has, as its basis, about a hundred years of combined data and experience. This background allows the structural design of the hull to be pursued by relatively well-proven design methods. Within limits, a hull form will be similar to previous hull forms, and the design is relatively forgiving to under or over-estimation of the loads. Any radical departure from the normal hull forms would severely de-value the usefulness of accumulated expertise, as knowledge of the loads and structural behavior is essential for design of the hull structure. These traditional approaches, as embodied many of the existing Classification Rules, are not necessarily the only way to provide the appropriate level of safety. The diversity of structural arrangements applied in yachts calls for a more direct approach to be taken in the assessment of yacht hull scantlings

Classification of loads
Any Classification Rules for yachts have to cover craft operating in a wide speed range – small planing craft to large, fast displacement craft, and moderately fast displacement craft. In addition, these craft can have different hull forms, see Figure 2, different modes of operation, and can be constructed indifferent materials, namely steel, aluminum alloys and composite. For the smaller craft parametric formulae, based on extensive service and theoretical experience coupled with model test results, have been used for a long time and they provide the sound basis in which the Rules are formulated. For larger fast craft, there is very little service experience and the design is mainly based on direct calculations verified by model experiments. For the typical displacement yacht, we can draw again on a vast basis of experience. Whatever the approach adopted, one should always verify the range of validity of the various formulae and direct calculation methods. They should reflect a unified philosophy, leading to a consistent level of safety.

A demand, capability and criteria approach to hull structural requirements
One key element in the development of design procedures is the prediction of the loads acting on the hull structure. These loads can be classified in:

- Loads associated with the support in vertical direction
- Sea loads
- Loads associated with propulsion, course keeping and maneuvering
- Loads associated with items or activities on board

The vertical support loads are strongly interconnected with the sea loads. Therefore, we will discuss them together first, and then the two other will be discussed shortly.

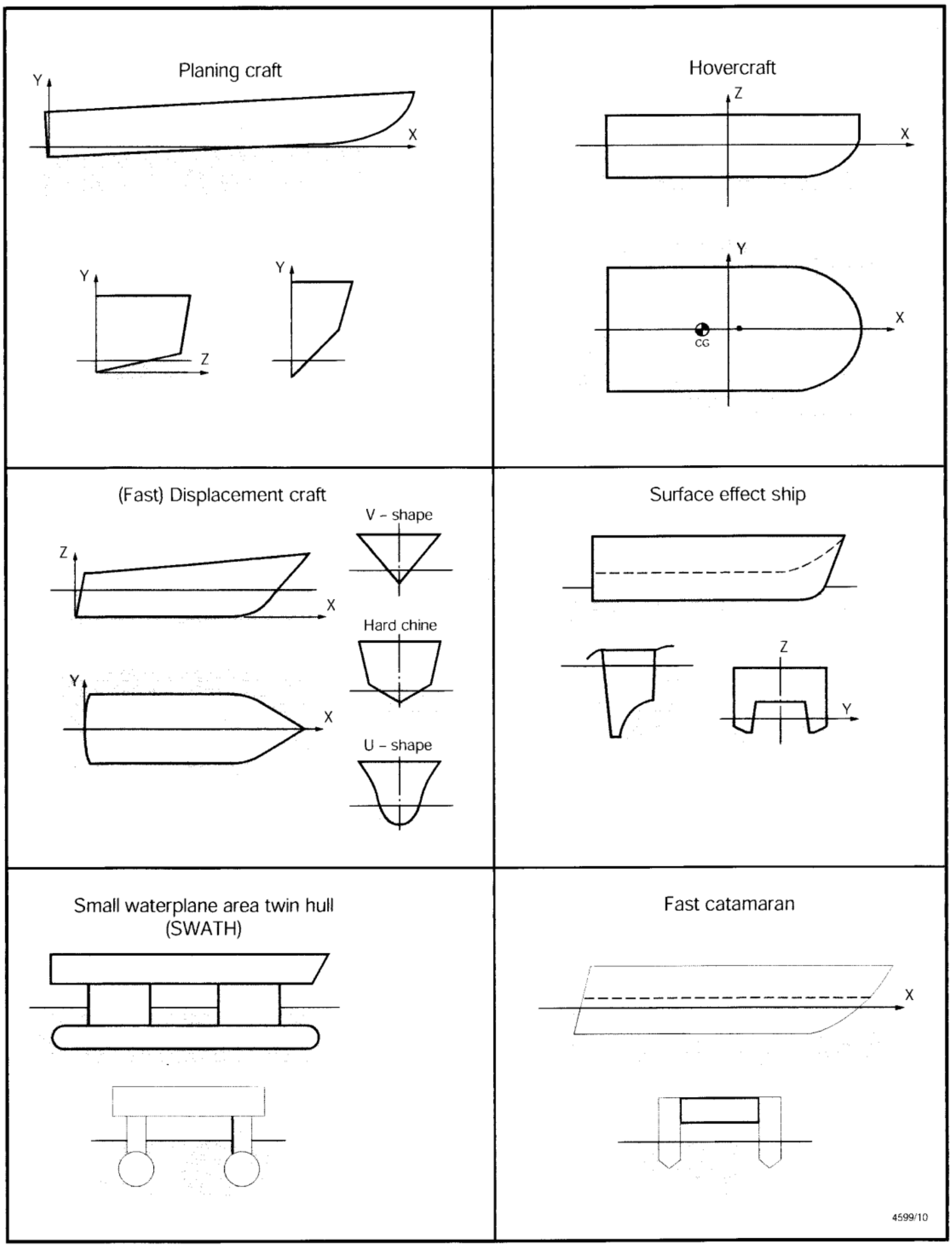

Figure 1 Different hull shapes

Vertical support loads
In operation a craft can be supported by three possible modes:

- Buoyancy force,
- Dynamic lift, and
- Air pressure.

Where the last support type is extremely interesting from a technical point of view, it has little application in the design of large yachts.

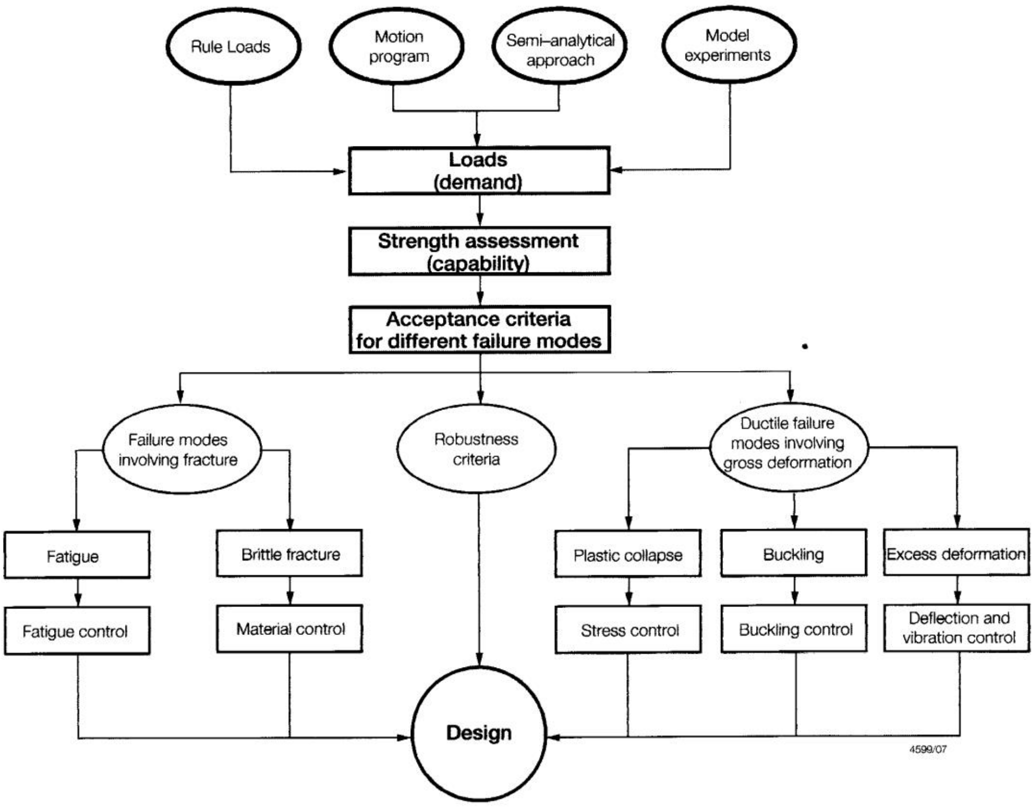

Figure 2 Design chart

A craft can experience a combination of all the above loads acting on the hull and their prediction is extremely complex. Therefore the Rules adopt the following approach:

Environment ➔ Demand ➔ Capability ➔Criteria

This decoupling of load, strength and acceptance criteria provides the opportunity to base the design approval on direct calculations using a similar approach, as illustrated in Figure 2. From a Class point of view, this is important, as while the Classification Rules should be as simple as possible to apply, the direct calculation approach should provide the same uniform technical standard for all kinds of craft while allowing for optimization by more detailed analysis. Whilst the strength assessment techniques (finite element analysis, for example) can be applied directly to all designs of the same material type, it is more difficult to establish design load formulations that are equally well adapted to all craft types, speed ranges and craft sizes. Equally, the acceptance criteria for metallic and composite constructions are quite - different. For large and high speed craft the main concern would be the determination of loads.

For high speed craft, the classification Rules introduce the key concept of an operational envelope. This is an outline of the limiting environmental and other conditions the yacht was designed for. The parameters controlling an operational envelope can include:

- range to refuge,
- limiting speed,
- limiting wave height, and
- limiting motion.

Such an operational envelope will form an appendix to the classification certificate, and should be placed in the *operational manua*l. In general, displacement yachts have no operational envelope assigned. They are considered suitable for world wide service, with the exception of ice infested areas.

The overall load on a craft consists of three components, namely primary, secondary and tertiary loads. The classification of loads as primary loads, which affect the hull as whole, secondary loads, which affect large components of the hull such as bulkheads, and tertiary or local loads, which have a local effect only, has been made for convenience in relation to structural considerations. This has resulted from the needs of the naval architect/structural engineer for a simplified approach to structural analysis problems. All loads, with the exception of thermal loads, originate from forces or pressures applied over small areas and whether they are subsequently treated in a local or an integrated form is largely a matter of analytical convenience. However, such a classification has been found to be useful in identifying the dominating forces for rule formulation and direct calculation purposes.

Primary loads
The primary load conditions which must be considered for the design of larger yachts are:

• Wave induced bending moment, dynamic bending moment and still water bending moment.
For relatively slow mono-hull motor yachts, the longitudinal wave induced bending moments are the most important loading, being most severe in head seas. For large fast yachts, the question of whether dynamic bending moments dominate the dimensioning of the structures remains open and has to be addressed for each case.
For conventional motor yachts with a steel hull, we have found that longitudinal strength considerations begin to dominate the structural design at a Rule length of about 50 meters, depending on the framing system, the method of construction and the presence of openings in the deck. At greater length, we generally see elastic failure modes ("buckling") take precedence and limit the allowable total sagging moment. In general, longitudinal stiffening of the decks is preferred when the length of the yacht is in excess of 50 meters.

The vertical bending moment load components do not, in general, dominate the structural design procedure multi-hull craft, where wave induced side force, transverse bending moment, and torsion loads are more dominant.

Motor yachts generally show distinct hogging bending moments in still water. The low prismatic coefficient calls for a narrow sectional area curve with most buoyancy located around mid-length. With the normally considerable overhang at the bow, and wide storage spaces at the stern, the deck is under permanent stretch, and this provides a certain margin against compression in the deck. It must be noted that for most large motor yachts there must be a hogging still water bending moment in all seagoing conditions. Consequently, when appraising loading conditions we need to look also at the condition with the LEAST hogging bending moment. This is contrary to common intuition, which would suggest that the maximum value is the dominant one.

• Fatigue loading
Because the majority of the loads imposed on craft are cyclic in nature, the possibility of failure by fatigue must not be overlooked, indeed most structural failures that have occurred during the service life of existing craft have resulted from fatigue. While there is a large body of knowledge on the fatigue performance of steel ships, very little research has been carried out and there is very little information available in relation to craft constructed of aluminum alloy or marine composites. The most important task in respect to fatigue life performance of the structures of high speed craft is the determination of the fatigue loading spectrum. The fatigue loading spectrum depends, of course, on the use of the craft. High speed service craft are normally intended to operate in a certain fixed service schedule, and this schedule, combined with the wave scatter data of the intended operation area, will give at least a reliable prediction of the fatigue loading. Most yacht owners like to operate their yachts as they like, and therefore it is very difficult to predict fatigue loads on a yacht. Therefore the only recommended solution is to stick to proven design details as given in classification Rules.

• Torsion load
For multi-hull craft consideration of torsion loads is equally important as that of the transverse loads, especially for the strength assessment of the cross-deck structures. The most severe torsion loads occur when the craft heading is such that it sustains quartering (bow or stern) seas. Class Rules provide deterministic formulae for the calculation of primary loads for the examination of hull girder and global strength.

• Rigging load
For sailing craft the loads imposed by stays and rigging may well be in excess of the loads imposed by waves. For a typical 40 meter sloop rigged sailing yacht the bending moment on the hull may be well in excess of the Rule wave bending moment, and consequently the sagging moment can be twice the Rule value. The stays normally are pre-tensioned to keep them in tension under all conditions. These tensile forces are counteracted by the mast compression, putting the hull girder in a classic simply supported beam loaded by a force at half length loading pattern.
Traditionally, Classification Societies consider the rigging as just an addition to the ship. Rule requirements aimed at minimizing the chance that failure of the rigging would impair the safety of the hull. Typically, the chain plate had to be stronger that the stay connected to it, and the chain plate support had to be stronger than the chain plate itself. The rig itself was deliberately left out of consideration. The yard, the owner and the designer decided between themselves what was best for them, and they had no need

for a Classification Society poking around into what was traditionally their own domain. Should it come to the worst, there was always the engine to take over.
This situation is about to change. First reason is the emergence of 'commercial yachts' in the market. A commercial yacht actually is a luxury passenger ship. The presence of 'passengers' on board has lead to regulations with regard to yacht rigging. Classification societies bring in their requirement sets for sailing passenger vessels. [2], [3],
Second reason is the development of new high strength materials and a desire for light construction, driven by the common availability of sophisticated calculation tools.
At this moment, there is no published calculation procedure for rigging loads. The existing construction Rules for passenger ship rigs are based on traditional materials, and they certainly need to be modified for application on modern yachts. In close co-operation with the yachting industry, Lloyd's Register is currently putting up a workgroup to develop relevant procedures.

Secondary and tertiary loads

The secondary and tertiary loads which must be considered for structural design are:
• Loads in a seaway due to external water pressures, including slamming and shipping of green seas. This category of loads is probably the most important from a local strength point of view, being the dictating criteria for the design of the small to medium size craft. In general the loads can be further sub-divided into the following components:

a) Bottom slamming
Bottom slamming arises as the result of the pitching and heaving motion of the craft at speed resulting in bow emergence and severe hydrodynamic impact loadings on re-entry. The impact is usually rapid and intense, generating a high pressure impulse on the bottom plating, which can be accompanied by a loud booming sound, particularly apparent for the larger size of craft. The duration of this type of impact force is, in general, less than100 milli-seconds. Bottom slamming has been the commonest cause of hull structural damages and its magnitude and duration depend on, and are sensitive to, the angle and relative shape of the hull to the water surface, and the encounter velocity and frequency. This is a complex phenomenon and while extensive research has been carried out in the past, no complete physical description is available yet. Worldwide this is one of the most intensively researched topics. The main focus has been in the domain of numerical motion and load computations. For now, classification Rules use empirical formulae based on the vertical acceleration at the center of gravity.

b) Bow flare slamming
Bow flare slamming pressures are associated with the rapid immersion of the upper flared portion of the bow into the sea. This is a more gradual phenomenon than bottom slamming, usually without any sound unless the flare is very concave, and lasting for less than a second. It nevertheless imparts relatively sudden and intense forces on the forward part of the craft. Bow flare slamming is an important consideration for high speed craft, especially for the displacement type craft. The main difference between bottom and bow flare slamming is that bottom slamming is always associated with the emergence of the fore body, while bow flare slamming is not. Experience gained from the design and operation of warships and fast cargo ships has provided some guidance for the formulation of load criteria, however more development work is required to be carried out making use this experience and data.

c) Cross-deck slamming
This type of slamming is an important consideration in the design of cross-deck structures for multi-hull craft. It arises as a result of the heaving and pitching motion of the craft causing the wave impact on the underside of the flat center body of the cross-deck structure. The loads sustained can result in large accelerations and related loads acting on the craft's structure, which must be catered for in the consideration of local and global strength. Classification Rules give an estimate of pressures, but in general the craft should be operated such as to avoid wave to bottom contact.

d) Green sea loading
The shipping of green seas on the upper deck forward is another source of transient loading that excites vibratory response and is caused primarily by the relative motion of the craft. In many cases this type of loading may simply be the static head of water scooped up by the bow until it runs off. The duration of this load therefore is relatively long. However there may be a dynamic component, especially if the ship is moving forward at high speed into head seas. In some instances, the whipping stress generated can constitute a sizable percentage of the total hull bending moment. Classification Rules provide deterministic formulae for the calculation of secondary and tertiary loads for design based on local strength considerations.

• Loads due to impact with solid objects and robustness considerations. This type of load is very difficult to estimate. Traditionally it has been taken care of by specifying minimum scantling requirements. It has been argued by many that existing requirements do not allow the full use of advanced materials and technology. However it is not an easy task to find a satisfactory alternative.
One aspect that could be taken in consideration is the potential consequence of failure. What happens if the plate is indented or ruptured locally. When the structural and watertight integrity of the yacht is not impaired, and the damage can easily be repaired in short time, it could be the owner's choice to agree on an intensified survey and repair program.

Other loads Other types of secondary loads, such as thermal loads, loads arising as a result of cargo (weight and distribution), craft motion and sloshing of liquids in tanks are important loading conditions which are required to be taken into account at the design stage. However these types of loading are common to all types of marine vessels and most of the calculation procedures for determining their values are relatively well established.

Classification Rules cannot replace good engineering and operating practice, and they generally take duly notice of this. For example, the Lloyd's SSC Rules say in Part 1, Chapter 2, Section 1.1.2:

> *1.1.2 The Rules are framed on the understanding:*
>
> *(a) that the craft will at all times be properly loaded. They do not, unless stated or implied in the class notation, provide for special distributions or concentrations of loading associated with the operation of the craft. LR may require additional strengthening to be fitted in any craft, which, in their opinion, would otherwise be subjected to severe stresses due to particular features in the design or operation, or where it is desired to make provision for exceptional loading conditions. In such cases particulars and details of the required loadings are to be submitted for consideration,*
>
> *(b) that the craft will at all times be properly handled, with particular reference to the placing on board of persons and equipment and the reduction of speed in heavy weather,*
>
> *(c) that compliance with the Rules does not relieve the designer of his responsibilities to his client for compliance with the specification and the requirements for the overall design and in service performance of the craft,*
>
> *(d) that the craft will not be operated outside of the parameters specified in any operational envelope which may have been assigned, without the prior agreement of LR.*

Classification Rules put up a formal framework for scantling assessment. The procedures account for most of the load components listed above, many of which are textbook items.
The art of structural design however is the translation from the loads into the structural responses.

Acknowledgements:
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References:

[1] Rules and Regulations for the Classification of Special Service Craft, 2002, Lloyd's Register

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