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WORKING LOAD TO BREAK LOAD: SAFETY FACTORS IN COMPOSITE YACHT STRUCTURES

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Abstract. The loads imposed on yacht structures fall broadly into two categories: the distributed forces imposed by the action of the wind and waves on the shell of the yacht, and the concentrated loads imposed by the rig and keel to their attachment points on the structure. This paper examines the nature of the latter set of loads and offers a methodology for the structural design based on those loadings.

The loads imposed on a rig attachment point vary continuously while the yacht is sailing. Designers frequently quote "working load", "safe working load", "maximum load" or "break load" for a rigging attachment, but the relationship of this value to the varying load is not always clear. A set of nomenclature is presented to describe clearly the different load states from the "steady-state" value, through the "peak, dynamic" value to the eventual break load of the fitting and of the composite structure.

Having defined the loads, the structure must be designed to carry them with sufficient stiffness, strength and stability. Inherent in structural engineering is the need for safety factors to account for variations in load, material strength, geometry tolerances and other uncertainties. A rational approach to the inclusion of safety factors to account for these effects is presented. This approach allows the partial safety factors to be modified to suit the choice of material, the nature of the load and the structure and the method of analysis.

Where more than one load acts on an area of the structure, combined load cases must be developed that model realistically the worst case scenario. In particular if the loading is quasi-static, the total loads on the structure must be in equilibrium. This is particularly important for Finite Element Analysis since an unbalanced load case can lead to excessive reactions at the points of restraint of the Finite Element Model. A method is presented for the development of a balanced load case for upwind sailing which allows significant insight into the behaviour of a yacht structure under "real" sailing conditions. The keystone of this approach is a method for constraining the model in a statically-determinate manner, to avoid adding unrealistic stiffness to the model.

Finally, once the structure has been built, it is sound practice to proof test it to give confidence in its reliability. The value of load for proof testing is a difficult choice but is made more straightforward by the rational approach to load definition presented in the paper.

1. INTRODUCTION

The loads imposed on yacht structures fall broadly into two categories: the distributed forces imposed by the action of the wind and waves on the shell of the yacht, and the concentrated loads imposed by the rig and keel to their attachment points on the structure. The concentrated loads are relatively straightforward to measure or calculate, allowing engineering calculation of the structure required to carry them. The distributed loads are much more difficult to define, so are usually dealt with by designing the structure to a classification society rule. This paper examines the nature of the concentrated loads and offers a set of nomenclature to describe how the loads vary as the yacht sails along.

This paper covers the reasons for using safety factors in structural design. Safety factors used in marine engineering, particularly by classification societies, are often hidden in the formulae used. Furthermore, most classification societies avoid defining the loads acting on the rigging. This paper suggests a clearer methodology for incorporating safety factors into the loads and material properties used for design, both by traditional methods and by Finite Element Analysis (FEA), and for the subsequent testing of the yacht structure to check its strength.

2. THE NATURE OF RIG LOADS

The loads imposed on a rig fitting vary continuously while the yacht is sailing. Designers frequently quote "working load", "safe working load", "maximum load" or "break load" for rigging attachments, but the relationship of these values to the varying load is not always clear. A set of nomenclature is needed to describe clearly the different load states from the maximum "steady-state" value, through the "peak, dynamic" value to the eventual break load of the fitting and of the composite structure. The system shown in Figure 1 has been used successfully for two decades for the design of composite yacht structures. It can be summarized as follows:

Table 1. Linked to figure 1

W1	Maximum steady-state load (flat water)
W2	Peak dynamic load (due to waves, gusts of wind, manoeuvres, sudden easing of sheets etc.)
LIMIT	Elastic limit of composite structure, Break load of rigging rod, fitting etc
ULTIMATE	Break load of composite structure

It should be emphasised that the W1 and W2 loads are the real or anticipated loads that will be applied to the structure, in other words they are the inputs to the load calculation. The LIMIT and ULTIMATE loads are the loads that the structure is designed to withstand, so are the inputs to the structural design, and are calculated from the W2 loads.

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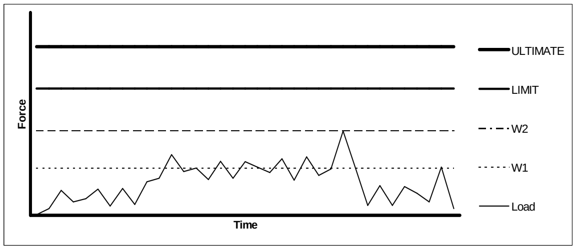

Figure 1.

The forces on a rig attachment vary continuously as a yacht sails along. With a load cell in suitable weather it is reasonably straightforward to establish the W1 (maximum steady-state) load. If that load cell is connected to a data logger, after many hours of sailing the W2 (maximum dynamic) load can be established.

The W1 load is frequently reached but the real load varies continuously around it. However it is a convenient load to define since it is easily measured. The right value for the W2 load is more difficult to establish; even if the load is measured for several years, there is no guarantee that the highest measured load would not be exceeded during the remaining lifetime of the yacht.

The most rigorous solution to this problem, pioneered by the aerospace industry, is to use statistical extrapolation to determine a W2 load that is sufficiently unlikely to be exceeded in the lifetime of the yacht (or aircraft)[1]. The more data is available, the closer this theoretical W2 load will be to the highest recorded peak load, for a given level of confidence. In the marine industry, years of load measurement would be prohibitively expensive and time-consuming, so fewer measurements are taken and the W2 load is chosen to be significantly higher than the highest recorded peak load.

3. SAFETY FACTORS: WHAT ARE THEY FOR?

Factors of Safety have also been called Factors of Ignorance. Their purpose [1] is to account for all the reasons that might make a structure fail if it was theoretically only just strong, stiff and stable enough to withstand the expected loads. These reasons might include:

a) Uncertainty in the load data: there is a small but real possibility that the load might exceed the chosen W2 load during the lifetime of the yacht.

b) Material variation: test values will always show some spread, but statistical methods can be applied to material test data to calculate the minimum strength of a material with a certain level of confidence. Composite materials in particular will show a wide spread of strengths, due to variations in void content, fibre volume fraction and resin mix ratio incorporated into the material during the manufacture of the component.

c) Geometric tolerances: a certain geometry will be assumed for analysis, but building methods will mean that the real structure will be different to some extent. Analyses of buckling and of Brazier (through-thickness tensile or compressive) stresses in particular will be sensitive to small changes in geometry.

d) Accuracy of the analytical method: a well-executed Finite Element Analysis (FEA) may allow the calculation of deflections to within a few percent of the true value, but stresses will be less accurate. Traditional calculation methods will usually give even larger errors, particularly for geometries that do not readily simplify to cases with an explicit analytical solution. Stress concentrations due to features not considered in the analysis (e.g. holes for fasteners) are probably the most common cause of inaccuracies in the calculation of stress.

e) Other effects that might not be considered explicitly in the analysis could include fatigue, creep, environmental effects (ageing), pre-stress due to manufacturing methods, damage in service, and so on. While these effects should be taken into account if they are going to have a significant effect on the structure, often it is considered sufficient just to use a factor of safety to cover them.

Clearly the choice of safety factor is critical to ensure that the structure is stiff, strong and stable enough in service throughout its design life, without being “over-engineered” to the point where its weight or cost (performance or financial) becomes detrimental. In assessing this balance, the engineer is making a judgment on the consequences of failure. In the aerospace industry this process is taken to its ultimate conclusion: safety factors are chosen to achieve an “acceptable” number of fatalities per passenger mile (hopefully a very small number)[1].

In the yachting industry structural failures are more common, which is considered acceptable because they are less likely to cause death or injury. In particular, rigging failures at a perhaps surprisingly high rate are accepted because the performance cost of making rigs “unbreakable” is too high and collapse of a mast is unlikely to result in fatalities. Similarly, the consequences of failure depend on where the boat is sailing: collapse of the composite structure is more life-threatening in the Southern Ocean than in the Hauraki Gulf. Thus margins of safety can be pared down much more in an America’s Cup yacht than in an Open 60 for the Vendée Globe.

4. HOW ARE FACTORS OF SAFETY APPLIED?

There are three common ways to incorporate safety factors in engineering analysis[2], illustrated in Figure 2.

4.1 Global Safety Factor: the simplest approach. One factor of safety is applied that accounts for every reason why the structure might be less stiff or strong in practice than in theory. Typically, engineers tend to use a factor between 2 and 6, although factors of safety of 18 or more[5] have been used for very safety-critical applications where there was considerable uncertainty about loads or material strengths. The factor of safety can be applied either to the loads (the “load factor” method) or to the material strengths (the “permissible stress” method). Whilst being extremely straightforward to use, these methods take no account of differences in analysis methods, material variability, load uncertainty or consequences of failure.

4.2 Limit State Design: the civil engineering industry often uses several “partial safety factors”, each of which accounts for a particular effect. Some partial safety factors are applied to the load and others to the material strengths. The structural design must meet two “limit states”: the Ultimate Limit State and the Serviceability Limit State[2].

a) The Ultimate Limit State requires that the structure must withstand the highest applied load without collapsing catastrophically. This includes material failure, buckling or overturning. The partial safety factors for this limit state are relatively high.

b) The Serviceability Limit State requires that the structure must not suffer excessive deflection, cracking, fatigue, vibration, fire damage or other degradation under its normal working conditions. The partial safety factors for this limit state are lower.

For example, a bridge might be designed with safety factors applied as follows for the Ultimate Limit State:

i) Partial safety factor of 1.4 on the “dead load”, i.e. the self-weight of the structure and any snow or ice on it. This accounts for uncertainty in the load, as the bridge might end up weighing more than anticipated.

ii) Partial safety factor of 1.6 on the “live load”, i.e. the weight of the cars, lorries and people on the bridge. This accounts for uncertainty in the load and for dynamic effects i.e. accelerations due to bumps on the road surface, walking loads etc. Because of differences in dynamic accelerations, this factor might be less for a train bridge than for a pedestrian bridge (especially in light of the problems with the Millennium Bridge in London). If the live load tended to lessen the likelihood of failure (e.g. in the case of a stone bridge where the load might stabilise the structure) a factor of 0.0 would be used.

iii) Partial safety factor of 2.0 on the material strengths. This accounts for ageing, fatigue, environmental effects, strain-rate dependence of properties, pre-stress and damage in service. The factor might be increased for materials with poor fatigue performance, poor UV resistance or for brittle materials.

iv) Partial safety factor of 1.5 on analysis of strength and stability. This accounts for geometric tolerances and inaccuracy of the analysis method. The factor could perhaps be reduced if FEA was used instead of traditional calculations.

For the Serviceability Limit State, the corresponding factors might be

i) 1.0 on the dead and live loads

ii) 1.0 on the material properties

iii) 1.0 on analysis of deflections and 1.5 on analysis of cracking of facings etc

The loads and material properties used in the analysis would be “characteristic” values, i.e. chosen statistically to encompass all but the worst 5% or so of likely values[2].

This approach is more precise than the “global safety factor” method in that it allows each influence on the analysis to be considered separately. However it is relatively complex to apply in practice because each of the safety factors have to be applied to every calculation. Note that the total safety factor on strength at the Ultimate Limit State is 1.6 x 2.0 x 1.5 = 4.8, similar to the global safety factor that might be used in the global safety factor method.

4.3 Simplified Limit State Design is an approach pioneered by the aerospace industry and now used in the marine industry. It is less complex to apply than the full Limit State Design method, because all of the safety factors except those to cover the material variability are applied to the loads. This is done at the start of the project. Thereafter, the safety factors need not be consciously considered again.

a) The expected loads on the structure are expressed as W1 and W2 loads (see Figure 1). The W1 and W2 loads are not used for strength or stability analysis but are used to check the structure for adequate stiffness.

Two (hopefully hypothetical) load states are then defined for strength analysis, the LIMIT load and the ULTIMATE load. At the LIMIT load there should be no degradation of the structure, in other words it should continue to perform as designed. Beyond the LIMIT load, the structure is allowed to yield, buckle, crack, etc provided that it does not fail catastrophically until the applied load reaches the ULTIMATE load [1,2].

The LIMIT load is higher than the W2 load (the highest load likely to be seen in service) by some factor, which accounts for *all* the issues raised above except the material variability. There is a further factor of safety between the LIMIT and ULTIMATE load states. The purpose of this factor is to ensure that, while LIMIT failures are rare, ULTIMATE failures should occur much less often. This factor is normally constant for a given structure, although it might be higher for an ocean-going yacht than an inshore racing boat.

b) The material properties used for analysis are “design allowable” values, which take into account the statistical variations due to processing techniques, environmental effects etc. Thus these properties should be reliably achievable in real structures built in a manufacturing environment (as opposed to a testing laboratory) and maintained over the expected working life of the structure. The above methods are compared in Figure 2 below. For the rest of this paper we will assume that the Simplified Limit State Design approach is being used for the design of the yacht structure

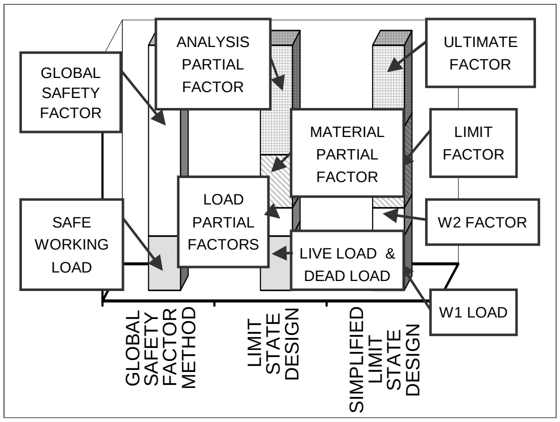

Figure 2: A comparison of methods for incorporating safety factors in engineering analysis

5. SIMPLIFIED LIMIT STATE DESIGN IN YACHT STRUCTURES

The steps required to apply the Simplified Limit State Design approach to yacht structural analysis are described below. The basic steps are:

a) define all the loads that will act on the yacht in a Load Table

b) define the material properties to be used for analysis as a set of Design Allowables

c) analyse the structure

5.1 Definition of loads

At the start of the design process, a load table is drawn up which gives the W1, W2, LIMIT and ULTIMATE values for each loaded fitting (see Figure 1).

a) The starting point is the W1 (static working) load, which can usually be measured, estimated from experience or calculated from first principles. The W1 load is multiplied by a factor to get to the W2 (peak, dynamic) load. This factor varies according to the fitting under consideration. For instance it might be around 1.6 for a backstay chainplate, but only 1.2 for a forestay chainplate, since slamming into waves tends to tighten the backstay but slacken the forestay, and because sudden easing of the mainsheet will momentarily increase the load on the backstay. Given sufficient time and money, the W2 load could be calculated by measurement and statistical extrapolation, but for most yacht projects the only practical method is to factor up from W1 based on experience.

b) Whilst the W2 load is theoretically the highest load that the structure will see, it is prudent to specify rigging and fittings that are somewhat stronger than this, to account for fatigue, ageing, and uncertainty in the load data. Hardware suppliers (e.g. Harken) tend to use a factor of 2.0 or more above the steady-state (W1) load[6]. Rig designers typically specify rigging that is at least 2.5 times stronger than the W1 load[7]. The break load of the fitting or rigging rod can then be used as the LIMIT load for design of the composite structure, since the rigging provides a “fuse” which will break at a reasonably certain load.

c) In the case of a sheet or halyard, where the hardware and ropes might be significantly oversized for stretch or handling considerations, their break load would be an excessive design load for the composite structure. In this situation the LIMIT load used for the composite structure should be just some factor above the W2 load, to account for geometric tolerances and inaccuracies in the analysis method or assumptions. For an aluminium airframe this factor might be as low as 1.0[1]. Such a low safety factor is justifiable only if the analysis methods are known from test results to be accurate and conservative.

For yacht design, the time spent measuring loads and designing the structure accurately enough to use such a small safety factor is usually not worth the weight saving, so the factor is usually much higher, perhaps 1.5 or more.

d) The load on the composite structure cannot usually be higher than the LIMIT load, since the rigging will break at this load. For some structures therefore, it is sufficient to make the composite strong enough not to break at LIMIT load. In practice however, if the fitting does break (for some unforeseen reason), one does not want to have to replace the hull structure in case it has been degraded in any way, even if it did not actually break apart. Thus it is usually wise to design for no *degradation* (e.g. resin microcracking of composites, yield of metals, or other non-catastrophic failure) at LIMIT load. This is particularly important for composites as micro-structural damage is so difficult to detect.

e) An occasional local yield or microcracking failure is more acceptable than a catastrophic failure. To ensure that the statistical likelihood of a catastrophic failure is even lower than that of a LIMIT failure, some further factor of safety is required. The simplest way to do this is to design the structure not to fail catastrophically at a hypothetical ULTIMATE load, which is greater than the LIMIT load by some factor. In aerospace, this factor is typically around 1.5[1]. In an inshore raceboat, where the consequences of structural failure are less devastating than they would be in an airliner, the factor might be reduced somewhat. On a blue-water cruiser, it might be significantly higher. Note that the ULTIMATE load cannot theoretically be reached because the rigging should break first, but it is a convenient tool for design purposes.

5.2 Material design allowables

Test results will give a spread of values that can be assumed to follow some statistical distribution (Normal[2] or Gaussian[1]) – see Figure 3. With sufficient test data, statistical methods allow material property values to be chosen which it can be assumed that nearly all future samples will exceed (say 90% or 99%) with a reasonable level of confidence (say 95%). In general, at least 5 test samples are required to give a reasonable level of confidence in the results[3]. Of course, even if 99% of the material in a real structure is stronger than assumed, 1% will be weaker. However, even if a small percentage of the material is slightly weaker than the assumed strength, the chances of this causing catastrophic failure are small, particularly where there are several (redundant) load paths and if it can be considered that the ULTIMATE safety factor includes a small margin to cover under-strength material[1].

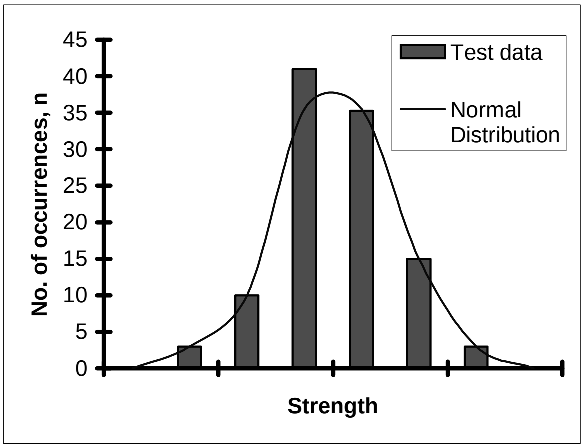

Figure 3: Illustration of a strength-frequency diagram showing the statistical spread of strength values of a hypothetical composite material

The strength of composite materials is more difficult to predict than the strength of metals, because the material itself is made as part of the component manufacturing process. It is clearly important that the tested material is made in a similar environment to the final component, ideally by the same people. Then the design allowable material properties derived from the test data should be reliably achievable in the boat yard.

5.3 Analysis

Having defined the loads and material strengths, the required scantlings of the structure can be calculated. Every likely mode of failure should be considered, including:

a) Excessive deflection at W1 or W2 load

b) Resin micro cracking or other non-catastrophic failure at LIMIT load

c) Fibre failure, bearing failure, interlaminar shear failure, through-thickness tensile failure, buckling, shear crimping or skin wrinkling at ULTIMATE load.

6. RESERVE FACTORS AND MARGINS OF SAFETY

A Safety Factor is a number that is chosen by the designer before the structure is designed or analysed. In practice, structural materials come in discrete sizes: there are standard ply thicknesses, sizes of extrusions and so on. Thus the analysis will show that if the structure is strong or stiff enough to satisfy the chosen safety factor, it will in fact usually be slightly stronger or stiffer still, and this extra is called the Reserve Factor (R.F.) or Margin of Safety (M.o.S.)[4]. These are defined as:

Reserve Factor= (actual strength / required strength)

Margin of Safety= (actual strength / required strength) – 1.*0

*M.o.S. is usually expressed as a percentage

Thus a structure with a Reserve Factor of 1.05 could be said to have a Margin of Safety of 5%.

Because all the required safety factors have been incorporated into the calculations, the designer should always be aiming for a R.F. of just over 1.00 or a M.o.S. of just over 0%. The tendency to design for higher margins than this should be resisted; if the designer feels more comfortable with a higher reserve factor, the safety factors built into the loads were probably too small.

Any given structure will have at least two Reserve Factors: the Reserve Factor over micro cracking or resin shear at LIMIT load and the reserve factor over catastrophic failure at ULTIMATE load. If there is a stiffness requirement at W1 or W2 load, there will be another Reserve Factor over this criterion. Likewise if the given piece of structure is subjected to more than one load case (for instance a keel structure subjected to heeling and grounding forces) there will be LIMIT and ULTIMATE reserve factors for each load case. All the reserve factors must be greater than unity (see Figure 4).

Since the factor between LIMIT load and ULTIMATE load for a given structure is usually kept constant, if the LIMIT strength of the material (i.e. the yield strength for metals or the micro cracking or resin failure strength for composites) is low compared to the ULTIMATE strength, the LIMIT reserve factor will be the critical one. Thus it is the material properties that determine whether the structure is LIMIT or ULTIMATE critical. Knowing the ratio between the LIMIT and ULTIMATE strengths for each material saves doing both calculations, since the critical case can be anticipated.

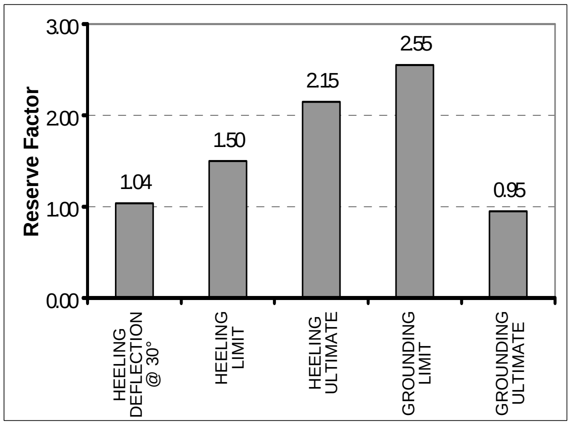

Figure 4: Illustration of Reserve Factors and Margins of Safety for a hypothetical keel grillage structure consisting

of longitudinal and transverse beams. The *deflection under 30° heeling load* is critical for the transverse members and close to optimum. The *ultimate strength in grounding* is critical for the longitudinal members, and insufficient.

7. COMBINED LOADS AND FINITE ELEMENT ANALYSIS

7.1 Combined load cases

With loads clearly defined in terms of W1, W2, LIMIT and ULTIMATE, it becomes reasonably straightforward to specify combined load cases. For instance, a shroud chainplate with the D1 and V1 shrouds attached to it must be able to withstand the break load of either rod. When one rod breaks, there will also be some load on the other rod, but probably not its break load. It would be reasonable to assume W2 load on the D1 shroud when the V1 breaks, so the combined LIMIT load case would be LIMIT V1 shroud load (i.e. the break load of the rod) plus W2 load on the D1 shroud. This LIMIT case can then be factored up as usual to get the combined ULTIMATE load on the chainplate.

7.2 Load cases for FEA

This approach can be extended to specify load cases for Finite Element (FE) models. A useful system is to run one “realistic” loadcase which includes all the W1 loads acting on the structure under some steady-state sailing situation, perhaps sailing upwind, as this is usually the case with the greatest global bending moment on the boat. In addition to this W1 loadcase, several LIMIT loadcases can be run, with LIMIT load applied to one fitting or rig attachment and W1 loads applied to everything else. That way, the stresses due to the LIMIT load are superimposed on the basic stresses due to the global bending of the boat, the rig pretension and so on.

These two types of load case are explored in more detail below.

7.3 W1 Equilibrium Load Case

Because all the W1 loads on the boat are maximum “steady-state” loads, they should all balance out so that the model is in equilibrium, i.e. not accelerating in any direction. Thus the sideforce on the sails should balance the lift from the keel, the mast compression should balance the tension in the shrouds and the sheets, and so on. This load case could therefore be called an equilibrium loadcase.

7.4 Restraints

Finite Element models need to be restrained in space even if all the forces acting on them are in equilibrium. There is as yet no FEA code that allows a yacht model to be restrained by putting it into a virtual sea and letting it sail along until it reaches a steady state; in any case such a model would take a long time to converge on a stable solution. In essence, what is required is a mathematical way to represent the force of the water on the hull, such that the buoyancy generated exactly balances the “weight” of the model, the drag exactly balances the driving force from the rig, and the lift of the foils exactly balances the side-force.

One way to achieve this is to represent the water by a number of spring elements connected between the yacht model and the ground. As the boat is pulled forward and sideways by the rig forces and downwards by its own weight, the springs will stretch to react against the movement, and if there are enough springs, the net effect will be something like the distributed forces due to buoyancy and drag. However the springs also add stiffness to the boat, so as the forestay and backstay tend to bend the hull, the springs will resist that bending and give the impression that the boat is stiffer than she really is. To minimise this effect the springs must be made very “soft”, but the movement of the model in sink and pitch is then very large under the imposed forces.

A better way is to restrain the boat with just enough restraints to take out the six rigid-body degrees of freedom (translation and rotation in each of the X, Y and Z directions). If only enough points on the model are restrained to remove the six degrees of freedom, no stiffness will be added to the model.

However, unless the applied forces are perfectly balanced, there will be some non-zero reaction forces at these restraints, which could lead to unrealistic local stresses.

A successful solution to this problem is to restrain the model using the rigging (see Figure 5). It will be assumed that the FE model consists of the hull and appendages, with the influence of the rig represented by forces applied at the rigging attachments. Five of the six degrees of freedom can be eliminated by restraining:

a) The two V1 chainplates in the direction of the V1 shrouds

b) The forestay chainplate in the direction of the forestay

c) The keel and rudder centres of lift in the direction of the lift vectors

This leaves the boat unrestrained longitudinally. In reality the boat accelerates until its drag balances the net driving force from the rig. The drag force when the boat is at full speed can usually be assumed to act evenly on the wetted surface of the boat. Since the keel top is approximately at the centre of the wetted surface for most boats, and the drag force is small compared to the other forces on the keel, restraining the keel top longitudinally is a simple way to eliminate the remaining degree of freedom. The stiffness of the keel structure means that the small reaction force at this restraint causes only small additional stresses on the model.

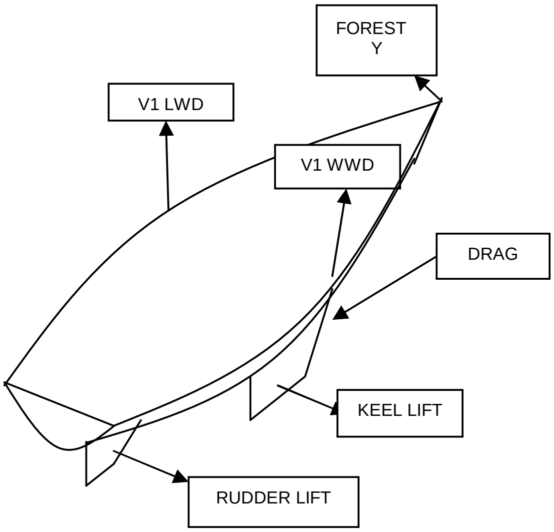

Figure 5: A statically determinate set of restraints for a yacht FE model

Once the six degrees of freedom have been restrained, provided that all the forces on the boat are in equilibrium, there will be little or no reaction forces at the restraints.

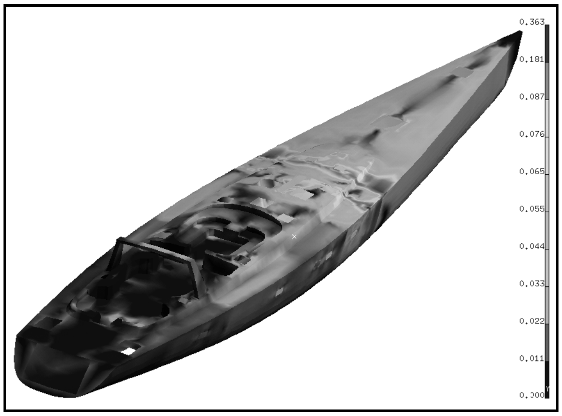

Figure 6: Strains on a yacht FE model subjected to the W1 equilibrium loadcase, sailing upwind on starboard tack. The strains on the foredeck are due to the global longitudinal bending moment from the rig. The highest strains on the deck are due to transverse compressive loads from the mast and chainplate bulkheads. The yacht is the Baltic 147, designed by Reichel/Pugh and engineered by SP Technologies.

7.5 Water pressures

Restraining the model in this way allows the water forces to be applied to the model as pressures on the hull surface. With the aid of Computational Fluid Dynamics (CFD) analysis, the pressure field can be calculated accurately for a given speed and angle of heel and trim. However, while many yacht development budgets allow for FE analysis, few can afford CFD.

Fortunately for the FE analyst, the pressure distribution on a yacht hull in flat water is approximately hydrostatic; the local variations due to dynamic pressure head make up a relatively small proportion of the net force.

Thus for the purposes of the FE model, the water can usually be represented by a hydrostatically varying pressure field. The water plane must be inclined to a suitable angle of heel and trim to balance the assumed rig forces and at sufficient sinkage so that the buoyancy balances the weight of the yacht.

Note that the water pressure distribution assumed can give a net force that balances the applied rig loads, but is not locally an accurate representation of the water pressure. In particular, the yacht's own wave system will reduce the pressure amidships and increase it towards the bow and stern, tending to increase the global bending of the boat slightly. This should be taken into account by modifying the pressure field if it is likely to be a significant effect compared to the global bending due to the rig (e.g. on a ketch or a schooner). Much more serious for the hull shell itself are the slamming loads from external wave systems; these need to be analysed separately and are beyond the scope of this paper.

7.6 Limit load cases and restraints

In addition to the equilibrium load case described above, to check the strength of local parts of the structure it will usually be necessary to subject the model to a LIMIT load case. This will almost by definition be a dynamic, i.e. non-equilibrium situation, so the system of loads and restraints used for the equilibrium load case will not be applicable. However, *St Venant's principle*[8] states that, provided the model is restrained sufficiently remotely from the area of interest, the method of restraint will have little effect on the local results. Thus it is usually sufficient simply to "clamp" the model away from the area of application of load, and ignore the stresses around the restraints[9].

8. PROOF TESTING

Demand for ever-higher performance pushes designers towards using smaller safety factors and relying on testing of the completed structure to check that the strength is adequate. Such testing allows weaknesses in the structure to be detected under controlled conditions, with the minimum risk of consequential damage or injury.

For a series production run of aircraft, it is economically worthwhile to test a prototype to destruction. For a one-off yacht, this is generally not the case, so the structure must be tested to a "proof" load that gives reasonable confidence in the structure's ability to support the anticipated loads, without damaging it during testing. This raises the question of what load to use for the proof test. By defining the loads in terms of W1, W2, LIMIT and ULTIMATE, the question is more easily answered.

Clearly, to avoid damage to the structure, the proof test load must certainly be less than the LIMIT load. To guarantee that the structure can withstand loads in service, it should be tested to more than the highest load it will see, i.e. the W2 load. Given that the factor between these two loads is generally small (of the order of 1.5) and intended to account for differences between analysis and reality, it is prudent to err towards the lower end of the range and proof test to W2.

There may be reasons why it is not possible to reach this load in a static proof test; for instance there may not be a suitable way to react the load in a static test.

It is also important to consider the safety implications of a structural failure

during proof testing, particularly where long lengths of loaded rope mean that a significant amount of elastic strain energy is stored in the structure.

9. CONCLUSIONS

a) The concentrated loads exerted on yacht structures by the rigging can be defined precisely in terms of the steady-state component of the load (the W1 value) and the maximum likely peak value of the load (the W2 value). This avoids the confusion caused by unclear terminology such as “maximum load” or “working load”.

b) A system of safety factors can be built into the loads used for structural analysis by the Simplified Limit State Design approach, which is based on the methods used in the civil engineering and aerospace industriel

c) The resulting LIMIT load state incorporates the safety factors required to ensure that inaccuracies in the analysis method, geometric tolerances and other effects will not cause the structure to be damaged at the highest load it is likely ever to see in use

d) The ULTIMATE load state is more severe than the LIMIT state by a factor that should ensure that, even considering the statistical spread of load data, the likelihood of a catastrophic (i.e. life-threatening) failure is acceptably low.

e) In conjunction with the load states defined in this system, the material properties for design must be based on a statistical analysis of test data to ensure with reasonable confidence that the material in the structure is at least as strong as assumed for the analysis. This is particularly important for composite materials due to the variability inherent in the manufacturing process.

f) The Simplified Limit State Design approach allows combined load cases to be defined for use in Finite Element Analysis.

g) Restraining FE models of yachts without adding stiffness or causing spurious stresses is not straightforward. A system of statically determinate restraints at the rigging attachments has been proposed to avoid these pitfalls.

h) The completed structure should, wherever possible, be “proof tested” to a suitable load. Usually this is the W2 load.

10. REFERENCES

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