Mega-Sailboats and Mega-Loads

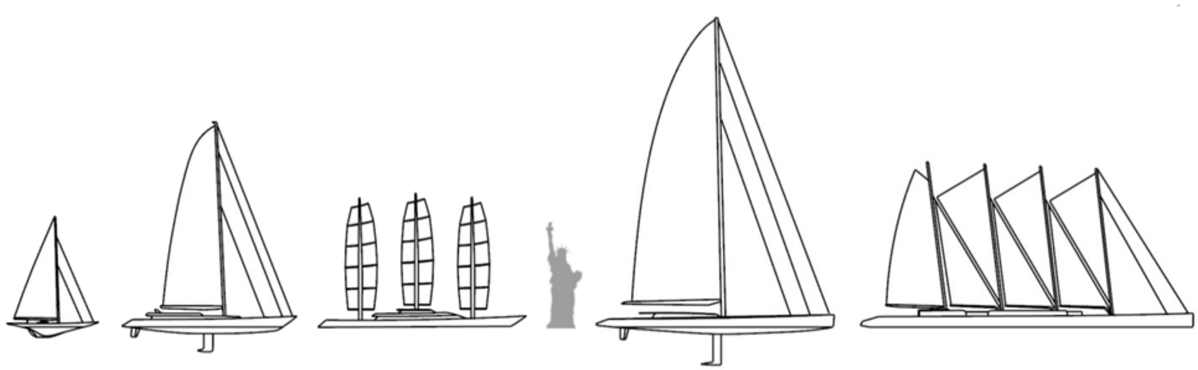
The upper end of the sailing yacht market continues to break records in size. The largest recreational sailing yachts the world has ever seen are currently under construction. Of these, four are to exceed 100 meters in length with the largest spanning a staggering 147 meters from bow to stern. Yet despite the 60% increase in size that this yacht boasts over its largest predecessor, plans have already been laid for even more enormous successors. Unfortunately, the challenges of building such vessels do not scale linearly with size. Pushing sailing yachts to these sizes presents greater engineering challenges in the handling of loads than when scaling motor yachts to this size. Computational analysis such as CFD (computational fluid dynamics) and FEA (finite element analysis) give yacht designers the necessary tools to design for these loads and to come up with innovative solutions to handling them.

While groundbreaking in size, this new fleet of giant sailboats will still join an already impressively sized fleet sailing today. The largest sailing yacht currently in service is the 88 meter modern clipper ship *The Maltese Falcon*. Launched in 2006, it has three enormous free standing square rigged carbon masts. Slightly smaller are the 83 meter three-masted schooner *EOS* (also 2006) and the 79 meter three-masted gaff rig schooner *Athena* (2004). Also launched in 2004 is *Mirabella V*, the largest single masted sailing yacht in the world at 75 meters long and the height of a 30 story building.

Maltese Falcon, Photo Onne Van Der Wal.

The current sailing super yacht fleet has set numerous records for size and loads on sailboats and has taught owners, project managers, yacht designers, sailmakers and others involved in these projects valuable lessons on how to design for and handle the enormous loads generated by these powerful rigs.

The current fleet is also paving the way for an even bigger breed of sailing yachts that are now under construction. The largest is the 147 meter *White Pearl* being built in Germany and due to launch in 2015. Slightly smaller is the four-masted 141 meter schooner *Dream Symphony* being built in Turkey from laminated wood and due to launch in 2016. Its colossal yet sleek wooden hull is housed in a 200 meter shed, one of many accommodations necessary to enable this new generation of mega-yacht. *Solar* is a 108 meter yacht with two masts similar to The Maltese Falcon. The smallest of the 100 plus meters yachts currently under construction is a 101 meter sloop that will have the tallest single mast in the world - a record previously held by *Mirabella V*.



The diagram above demonstrates the progression of sailing yacht sizes. Shown from left to right is a 38 m 1930's era J-Class yacht, 75 m Mirabella V, 88 m Maltese Falcon, 101 m super sloop and the 141 m Dream Symphony.

Building sailing yachts on this scale presents engineering challenges unlike those found in building equivalently sized motor yachts. The unsteady nature of the forces on a sailboat's rig in addition to the constantly changing geometry of the sails mean that sail handling systems need to be designed for numerous loads cases and for many possible geometry configurations. On smaller sailboats, sail handling systems are often overbuilt to account for these unpredictable loads. Simply scaling these overbuilt systems up does not work because the weights become excessive. The fact that sails are only stable structures when set properly to the wind adds to the challenge of properly designing for maximum loads.

The new breed of sailing super yachts is also being pushed harder by their owners and crews with the emergence of competitive super yacht regattas around the world. Early sailing super yachts were designed primarily with comfort in mind and thus were not pushed to the strength limits of their designs. The super yacht regatta series has raised the bar for the performance of these boats and now they are being designed with racing in mind. Though the yachts will spend most of their lives leisure sailing they are designed for the loads encountered while racing. Load definitions are similar to race boat programs with the rig power usually being limited by the boat's maximum righting moment.

Aerodynamic Loads

The aerodynamic forces on the sails and the reaction loads in the rig scale with the square of a sailboat's length and with the apparent wind velocity. This leads to enormous loads imparted to the rig, sails and running rigging of these mega sailing yachts. With sheet loads reaching 100 tons and mast compression loads reaching 1,000 tons, accurately predicting these loads is critical both for both design and operational safety.

In past wind tunnel testing, real world data scaling and simple force balances have be used to model rig and sail loads. However, these techniques are not accurate enough for the design of the new breed of mega sailing yachts. All of these techniques require many simplifying assumptions about the geometry being studied. Today, yacht and sail design offices use high resolution CFD and FEA to accurately model the aerodynamic forces created by the sails and the resulting structural loads in the rig. Armed with knowledge from these computational studies, rig and yacht designers have found innovate ways to handle these enormous loads safely and efficiently.

Computational Studies Used to Optimize Structures

While load estimates based on force coefficients are useful for initial design purposes unless the force coefficients have been derived from extensive model testing on the exact yacht geometry many simplifying assumptions need to be made about how the aerodynamic forces are applied to the rig and how the rig reacts to those forces. This leads to designers needing to build in high safety factors to account for the uncertainties in the details of the loads.

Today yacht and sail design offices are starting to use high resolution computational fluid dynamics and finite element models to accurately model the aerodynamic forces created by the sails and the resulting structural loads in the sails and rigs. Computer technology and simulation codes have now progressed to a point where it is practical for yacht and sail designers to create detailed coupled RANS CFD-FEA models for new and existing sailing yacht projects in order to predict loads. The detailed nature of coupled RANS CFD-FEA simulations makes it possible to incorporate all of the relevant geometry and physics involved in sailing yacht load analysis reducing much of the uncertainty in the analysis.

In order to save weight and money final structural designs are often optimized using coupled CFD-FEA simulations in order to optimize both the weight and the cost of structural components. As an example a recent project we worked used a detailed parametric model of a sail furling mandrel to decide whether or not to add another $100,000 of carbon fiber into the mandrel or not. Using a standard force coefficient analysis lead to the mandrel being 1.5 times heavier than the detail computational analysis showed that it needed to be. This procedure can be applied to all the major structural components of the rig such as the mast, deck hardware and rigging. The optimized structural designs can be safe and millions of dollars cheaper than what would be possible to design with lower resolution force estimates.

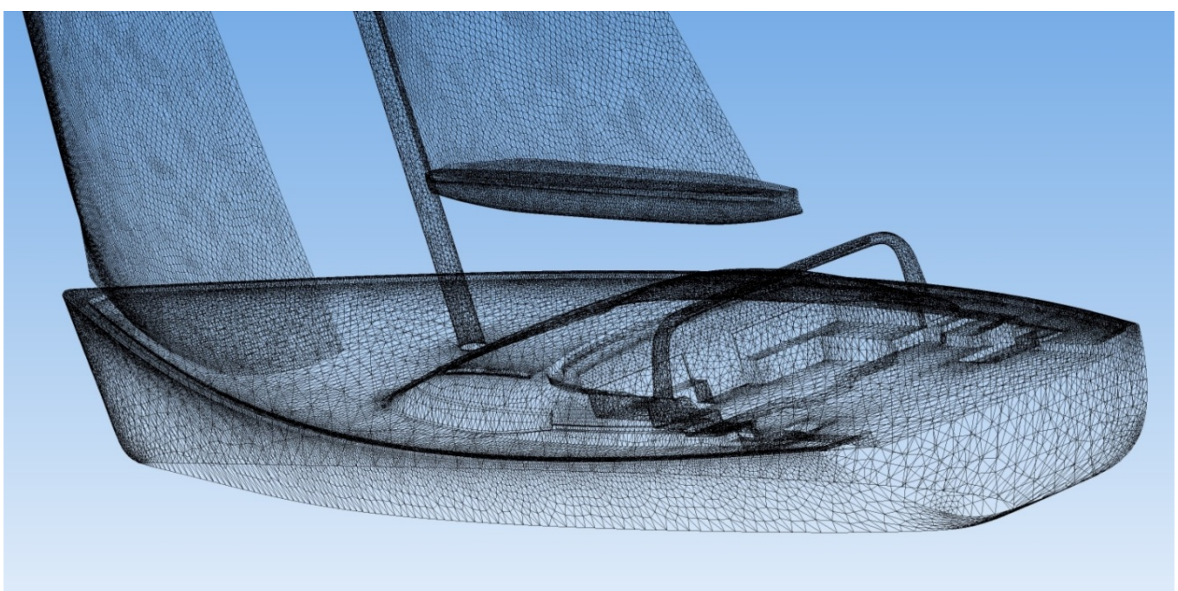
Coupled RANS CFD-FEA Simulations

Coupled RANS CFD-FEA models are setup using a base geometry that defines the geometry for both the CFD and FEA models. Surfaces pressures and shear forces are solved for in the CFD model and transferred to the FEA model across the models surfaces. In this way the details of the fluid flow geometry and the mechanics of the structural components interaction can be accurately modeled. Turbulent flow is present everywhere in sailing simulations so it is important to use RANS CFD in order to capture important turbulent flow phenomena like flow separation and viscous wake effects. Structural non-linearity is also present in most sailing simulations and thus nonlinear FEA must be used.

The analysis codes have been capable of analyzing large yachts using these techniques for some time however these simulations are computationally expensive and only recently have powerful parallel processing workstations and clusters come along at prices affordable by design offices. To properly resolve the mesh for a RANS simulation of a 60 meter sloop including all the major geometry using Fluent requires around 15 million grid cells.

Geometry Modeling

Accurately modeling the detailed geometry of a yachts rig and sail configuration is one of the biggest advantages of this type of analysis. Designers are able to accurately set the boats rig and sail geometry up virtually and define loading scenarios likely to be experienced in real life. The starting point for a computational load analysis of yacht is a detailed three-dimensional CAD model of the yacht and rig. If three-dimensional CAD files are not available for the project step one is to define the CAD model starting from 2d drawings. Sails are then designed by a sailmaker to fit the rig and incorporated into the 3d model of the yacht. Sail sets are defined to choose what sails are to be used in what apparent wind conditions.



RANS CFD surface mesh for a 125’ sailing yacht.

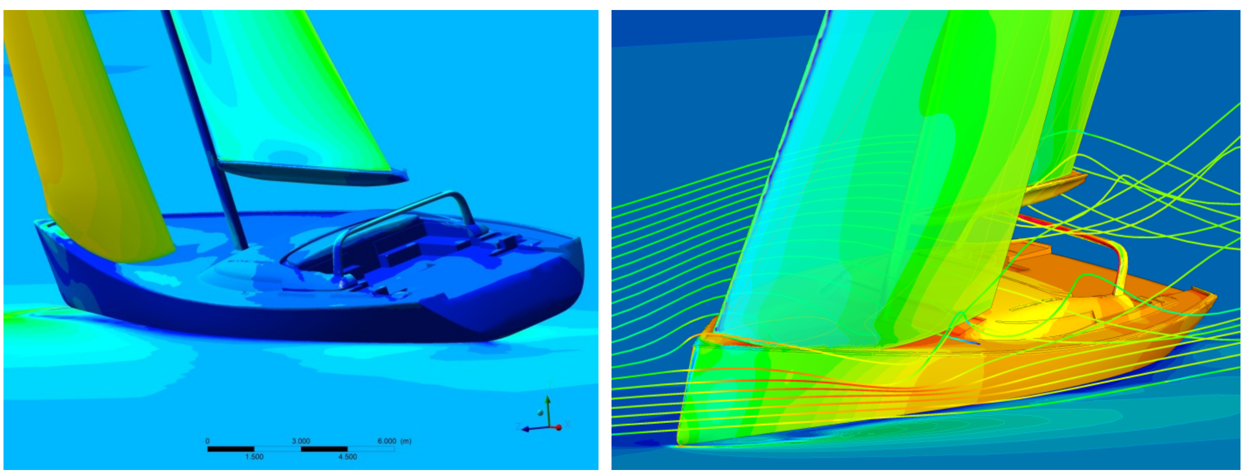
Load Case Definition.

The next step is to determine at what apparent wind angle and wind speed the load calculation will be performed at. Often in the design stage yacht designers use a velocity prediction program or a VPP to predict the speed, heel, yaw, pitch and roll of a yacht given a true wind direction and a true wind speed. VPP's solve the equations of motion for the yacht and are used to study a yachts performance throughout the range of true wind angles and speeds the yacht will sail in. VPP's are used to determine in what conditions the boat becomes overpowered. Generally the maximum loading a yacht will see occurs then the sails are producing a heeling moment equal to the maximum righting moment of the yacht. From these VPP studies maximum loading conditions are established and used for input into the coupled CFD-FEA analysis.

RANS Simulations

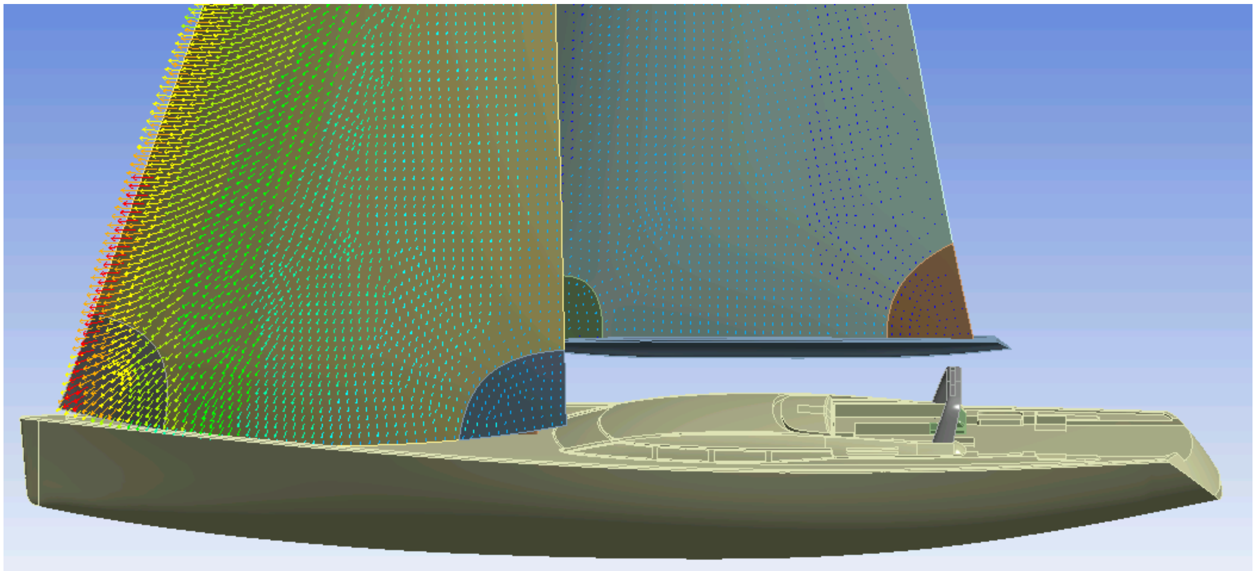
Once the apparent wind speed and angle have been set for a load analysis a RANS CFD calculation is performed to solve for the aerodynamic forces on the sails and other structures. RANS CFD models yield surface pressures and frictional shear forces on all the surfaces as well as the detailed flow patterns in the volume of air surrounding the boat. Post processing RANS results from max loading runs can give the designer valuable information about flow conditions producing the maximum loads. The results can show details of the flow such as when the sails are stalled, when unsteady wakes and vortices are present and how various components interact aerodynamically.

There are many RANS codes used for the analysis of sails and rigs. We mainly use Fluent, but CFX, Star CCM+ and OpenFOAM are often used. There are a number of proprietarty RANS codes in use as well.



RANS CFD surface pressure and shear force contours.

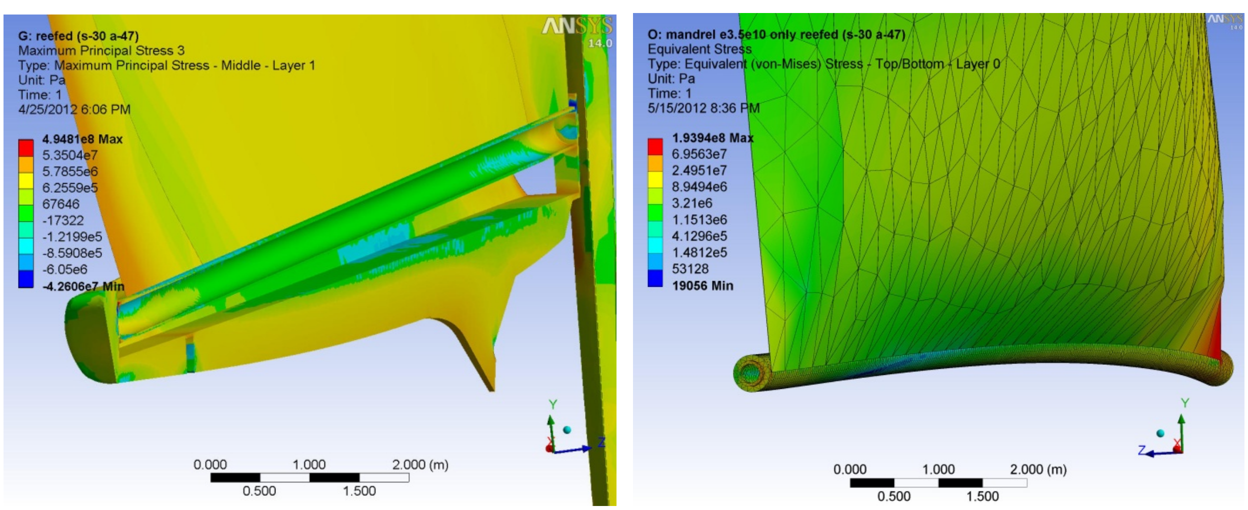
The surface forces are then transferred to the FEA model across the surfaces. The surfaces serve as the interface between the fluid volume forces solved for in the CFD model and the solid stresses and displacements solved for in the FEA model. Since the CFD and FEA models have separate meshes the surface forces from the CFD analysis must be interpolated to the FEA grids. This procedure works well but a slight loss in forces can occur.   Proper definition of all included faces in the model is an important part of both the CFD and FEA analysis setup.



Surfaces pressures imported into FEA model shown as vectors on the sails.

Nonlinear FEA Simulations

Many of the flexible structures used in yachts such as sails, masts, mandrels and cables behave nonlinearly when loads are applied and thus non-linear FEA codes must be used to analyze them. Non-linear FEA codes iteratively solve for structural displacements enabling the loads to change as the geometry deforms. Capturing this behavior is important for the membrane calculations on sails, the reaction of cables that can go slack when no load is applied and the bending of masts, booms and furling mandrels.

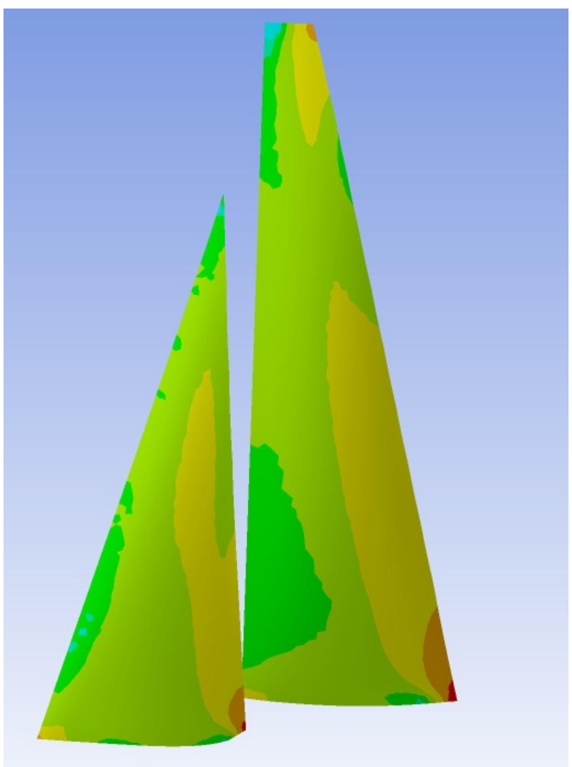


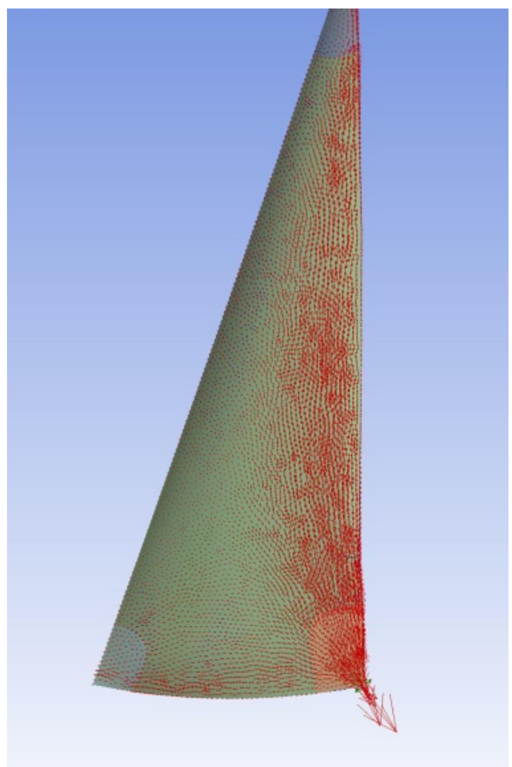
Non-linear FEA analysis of a bending mainsail furling mandrel. In this case a non-linear model was needed because the flexibility in the mandrel caused very different initial and final loading states.

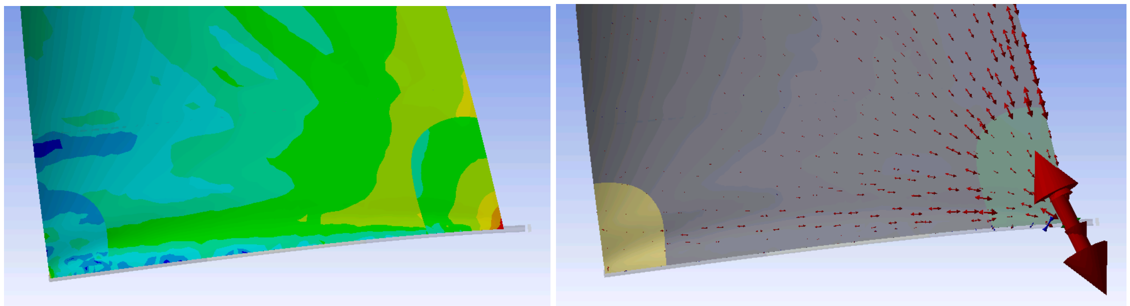
There are two types of reaction loads that are important to the sailing load analysis of yachts. The first is the membrane loads in the sails that are used by sail designers to engineer the sails. The second is the reaction loads that the sails impart to the rigs that are used by the yacht designers to engineer the hardware that the sails attach to.

Membrane Loads

Membrane loads are modeled using nonlinear shell FEA elements. Sails are constructed from layers of woven material or laminate cloths made with load bearing fibers sandwiched between sheets of plastic film and reinforcing fibers. Depending on how detailed a load analysis is being performed the sail material can be defined either isotropically or by oriented layers of orthotropic material defined by the structure of the material and how it is arranged in the sail. Patches, battens, corner and edge attachments are added to the models as needed by the analysis. When detailed analysis is performed on the sails it is important to resolve nonlinear behavior such as folding and load realignment. Sail designers use the membrane loading information to select materials and also to help determine the panel and fiber layouts in the fabric. Maps of stress paths in the sails that come from the FEA models are used to minimize the needed fiber weight and costs in laminate sails by aligning fibers with load paths.





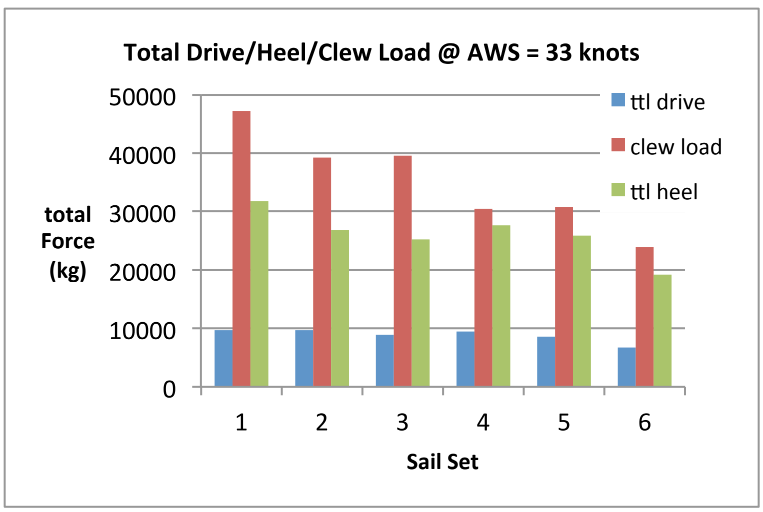


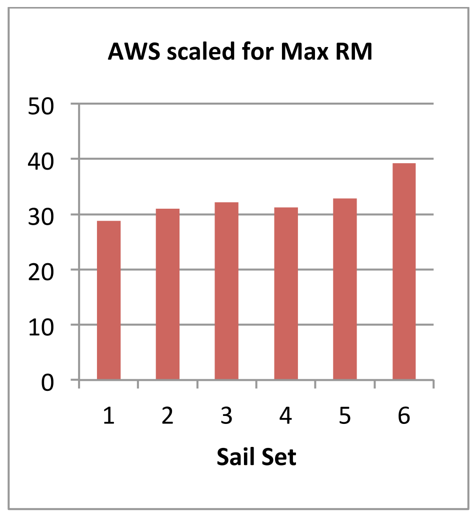
Membrane stressed visualized on the left with contour plots and on the right with scaled vectors of max principle stress.

Rig Loads

The second type of reaction loads important to sailing load analysis is the reaction loads placed on the rig by the sails. For initial design studies sail corner and edge loads can be used as input into rig component FEA models. For final design the reaction of the sails and rig can be solved for together in one model that captures the details of the sail-structure interaction.

One common use for rig load analysis is to accurately define the maximum load sheeting and sail setup configuration. Below are charts from an upwind mainsail clew load analysis of a 60 meter sloop. Six sail sets were defined for an upwind sailing condition ranging from tight trim in sail set one to looser trim in sail set six. Going from sail set one to six the main traveler is eased six degrees and the twist in the main and jib are increased by 50%. Sail twist refers to how tightly the sections of a sail are trimmed relative to the bottom of the sail and easing the sheets has the effect of increasing flying shape twist. In this study we were interested in estimating the mainsail clew load at 33 knots apparent wind speed with various settings and determining up to what wind speed the various setting could safely be used. It was found that the tightest configuration could handle an apparent wind of 30 knots before becoming overpowered while the loosest trim to be carried almost up to 40 knot apparent wind speed. Detailed studies like this are only possible when all relevant geometry and loads taken into account.





Results from a detailed upwind load analysis showing at what wind speed different trim configurations can safely be used up to.

High Load Design Solutions

Through experience with the current generation sailing mega yachts and aided by detailed structural studies such as coupled CFD-FEA analysis sailing mega yacht designers have found a number of practical and innovative ways to handle these huge loads.

Free standing rigs

The use of rotating free standing rigs such as the DynaRigs used on the Maltese Falcon is one way to greatly reduce the compression loads that the rigging imparts on the hull. Conventional masts are thin columns that are supported with support stays. In order to produce the wanted lateral and longitudinal support the stays also impart a large compression force on the mast and large internal structures are needed to handle such loads. One way of reducing compression loads is to use a free standing mast. Free standing masts can be thought of cantilever beams that support bending using their inherent stiffness not the support of wires. The down side of large fee standing masts is that they need to be extremely strong.

Rotating free standing rigs are designed to rotate all at once around a central bearing. This creates challenging engineering for the bearing and mast designs but creates simple sail controls and no need for sheets to control the sails. One of the biggest hazards to crews of large sailing yachts is flogging sails and sheets and the rotating masts solve this problem.

Advanced Furling systems

Well thought out sail furling systems are important for dealing with the large loads present on sailing superyachts. At this scale it is not practical to have sails that are raised and lowered each time a boat goes sailing. Instead the sails are furled along mandrels that are recessed in cavities in the mast and booms and along foils on the head stays. Furling systems today are robust and capable of furling sails when needed with little human intervention. Captive winch systems like found on commercial ships are used both in the furling and sail sheet handling on large sailing yachts.

Downwind Sails

Downwind sail handling at this scale is a much greater challenge than upwind sail handling. Unlike upwind sails, that are relatively stiff and supported in all the corners and along at least one edge of the sail downwind sails such as spinnakers are usually only supported in the corners. Spinnakers act like parachutes as drag devices instead as wings like upwind sails. This means that they work in a very turbulent, unsteady flow field. In order to fly or properly inflate the control lines attached to a spinnaker must be constantly adjusted to account for the changing flow. If the control lines are not adjusted perfectly the spinnaker will collapsed and re-inflate creating hazardous conditions for the crew and boat.

Because of the sail handling problems spinnakers can create they are used only in light to moderate conditions on large yachts. Hybrid upwind-downwind sails known as code zeros have been developed that have large areas like spinnakers but are more controllable like a conventional headsail. Code zeros are supported only in the corners like spinnakers but have a strong torque rope attached to their leading edge that acts like a stay supporting the sail when loaded. When you are done with a code zero it is furled around the support torque rope and then lowered like a spinnaker. Torque ropes are special ropes design to provide much more torsional rigidity than a typical rope to allow for the sail to be furled.

Lighter Rigs and Sails

The use of advanced fiber composites such as carbon fiber in the rigs of super yachts has greatly reduced the weight of the rigs enabling the boats to have more stability and make the moving parts safer. Carbon and other advanced fibers are used both in the solid laminate constructions such as mast and booms but are also used for the standing and running rigging. Sails are usually made from flexible laminates that minimize weight by only concentrating load bearing fibers only where they are needed.

How large can Sailing Mega Yachts Get?

The 101 meter sloop that is about to go into construction is probably getting close to the limits of today's technology for single masts. The mast will be over two times longer than Boeing's 787 Dreamliner's wing span. Like with all large structures rig weight often becomes the limiting factor in size.