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Scantling of Mast and Rigging of Sail Boats: a Few Hints from a Test Case to Develop Improved Design Procedures

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Abstract

In this paper, the structural design of mast and rigging of sail yachts is presented from a practical viewpoint, highlighting main idealization concepts of structural behavior. At first, the analytical procedures available in open literature are briefly reviewed, considering current industrial practice in scantling design of sail yachts. Applicable rules are considered as well.

Then, more complex scantling procedures, taking advantage of modern computation facilities, are presented. Indeed, finite element (FE) analyses are more and more routinely used by designers. However, large deformations and slacking behavior of rigging and sails require nonlinear calculations, making convergence of algorithms difficult. In this case, limit states should be carefully defined; description of environmental actions and loads application on the structural system need engineering judgment, skill of FE analysts and sailing practice to completely understand the performance of the structure.

Examples of applications on a typical modern sail yacht highlight that the design of these fascinating slender structures is really challenging and their design is still largely based on empiricism.

Keywords

Mast; rigging; sails; FEM; scantling; assessment.

Introduction

The sail system behavior is a typical fluid-structure interaction (FSI) problem, being the acting loads dependent on the structural deformations. Moreover, it is complicated by the fact that two fluids are in principle involved: water and air. As in many other engineering fields, racing is supporting the progress. Nowadays, technological innovations have introduced large improvements in sail yachts. The work of riggers and sail-makers is more and more becoming a high-tech job in collaboration with skilled aerodynamicists and material scientists. Studies have been widely developed and it is often possible to see high-tech sails even on cruising boats used for local yacht club regattas.

Limit states differ from those of traditional ship hull scantling as buckling is the governing phenomenon for such slender structures. However, yielding and ultimate strength (collapse) should be considered as well, taking into account that weight optimization is of paramount importance because of its effects on ship's stability and seakeeping performances. Fatigue is also a challenge for relatively large masts built by welded plates in lightweight alloy and for fittings like turnbuckles, toggles, eyes terminals and tip cups at spreader ends.

Mast and rigs are essential parts in sail yachts for various reasons, not least the fact that any rig failure may have catastrophic consequences for the ship and her crew. However, while many aerodynamic studies are carried out on masts, rigging and sails to optimize their shapes, rather small efforts are devoted to the structural ability of mast and rigging to deform in a controllable manner and even less to the fluid-structure coupling behavior, including sails as structures.

Different from the usual practice of yacht hull scantling, whose rules are well calibrated allowing a rather detailed structural design by applying simplified formulations, the design of a typical sail system is currently assessed according to various methods. Starting from very approximate analytical procedures, the design may be refined up to a complete numerical structural model, able to consider complicated structural behaviors of mast and rigging and even of sails and their structural and fluid couplings (FSI). Applied methods depend on boat size and type, performances, etc., but especially on budget and availability of computation facilities.

In the following, an overview of various methods is presented, showing their approximations and capabilities and including the results of a test case.

Structural concept of sail systems

Basically, the rig of a sailing yacht is a pretty simple structure composed of beams and cables, though subject to large deformations due to its slenderness. The mast has the typical beam-column behaviour, being axially, longitudinally and transversally loaded; its bending is balanced by suitably tensioned shrouds and stays. Spreaders reduce the unsupported mast length. A higher number of spreaders increases the transversal mast stability. In addition to fore and back stays, sometimes runners, i.e., lateral backstays linked approximately in the upper midspan of the mast, are fitted to counteract the bending effect of spreaders and excessive longitudinal deflection due to inertial loads. The forestays are made straight under foresail(s) loads by tensioning backstay(s) or runners. Geometrical nonlinearities, i.e., large deflections, implying change of load directions, and nonlinearities due to null compressive stiffness of cables and sails are the peculiarities of these structural systems. Fig. 1 shows the main components of the mast and rigging of a sail boat.

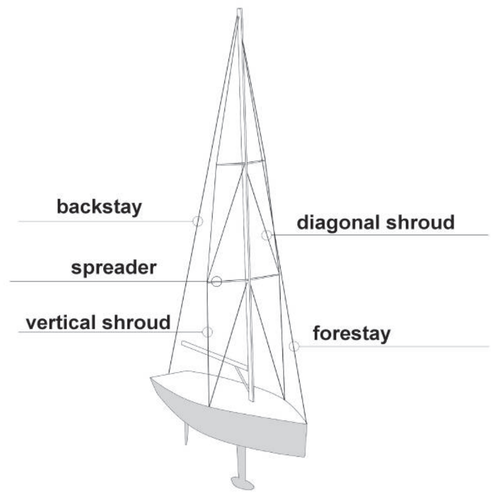

Fig. 1: Mast and Rigging Nomenclature (Bruni, 2007)

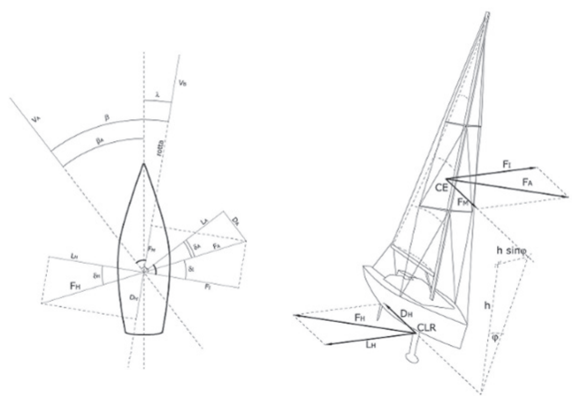

Fig. 2: Righting Moment/Sail Loads Equilibrium

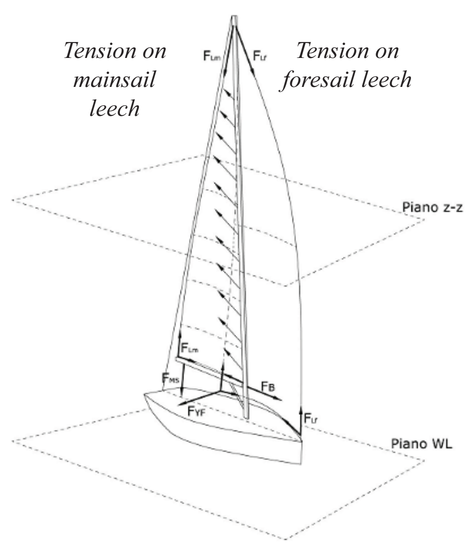

Fig. 3: Loads from Mainsail Pressure (Bruni, 2007)

Close hauling and running/broaching under spinnaker are generally considered to load the mast at sail connections, though others scenarios must be accounted for. Loads of sheets and halyards, basically depending on tension of sails leech and luff (i.e., the aft and fore edges of sails), need to be estimated as well.

Boundary conditions of the structure should be carefully defined. The mast may be simply supported or clamped at deck level, depending on where it is stepped, i.e., on deck or on keel passing through the deck. Shrouds and stays are hinged to the hull by means of chain-plates; hull deflections should in principle be considered as shrouds or stay ends may become closer, loosening their pre-tensioning. The hull bending effect is comparatively larger for rods which are stiffer than steel wires because of their different apparent stiffness modulus, but it is generally neglected in standard design procedures.

Design methods overview

Analytical methods and rule requirements

The scantling practice of sail yachts, other than very large or racing ones for famous and sponsored regattas like the America's Cup, is mainly based on a few prescriptive analytical procedures. Indeed, applied design loads are still affected by rather large uncertainties and are empirical to a large extent.

It is also common practice that transversal and longitudinal behavior of rigging are analyzed separately in simplified design procedures, even if this is not the case because of the effects of swept spreaders, for instance.

The literature presents a number of empirical design criteria. As a trivial rule of thumb, for very small sailboats without spreaders, the compressive load on mast may be assumed equal to boat displacement while rigging shares the tensile reactions in a statically determined truss frame. For larger yachts, the equilibrium of the heeled ship is traditionally assumed as the starting point for a quasi-static approach, hence separating the hydrodynamic actions from the aerodynamic ones. Compression on mast and tensile axial forces on rigging is then computed by assuming various load distributions on mast and rigging equilibrating the righting moment (RM) of the boat (see Fig. 2). Longitudinal loads on mast coming from stays, sheets and halyards are empirically considered, setting the value of the sag of sail edges (i.e., assuming the funicular polygon behavior).

All analytical procedures for rig design found in open literature are more or less based on the well-known Skene's method (Kinney, 1962), i.e., on ship RM, with variations to take into account the modeling assumptions and effects like distributed forces from sails, halyard forces, and longitudinal forces from stays. The global longitudinal bending of the mast is only implicitly accounted for by safety coefficients, rather than coupling the compression and the bending behavior.

A rational engineering approach is generally applied to distribute transverse rig loads due to sail forces on mast and rigging in different sailing conditions and equilibrating the corresponding RM. The usual simplifying assumption is that the ratio between main sail force and genoa force is the same as between their sail areas. Moreover, for triangular sails, 3/7 of the sail force acts at the head and 2/7 each at tack and clew; for spinnakers 4/10 at the head and 3/10 each at the clews. The compression at mast step is approximately distributed as 50% due to shrouds, 40% due to stays and 10% due to halyards. Loads are usually idealized as concentrated forces, although mainsail acts along luff applying a distributed load as shown in Fig. 3. Mast manufacturers often use their own scantling procedures, extended and calibrated by their own experience.

In a preliminary approach, 1-D structural idealizations using trusses and beams seem sufficient, even if some limit state assessments require advanced modelling (e.g., local buckling, collapse, fatigue). Thus, the cornerstone of the mast design is the ability of the mast designer to define loads, corresponding distributions and boundary conditions representative for critical/extreme scenarios.

Mast tuning is of paramount importance for the structural behavior. Shrouds and stays are pre-tensioned to avoid excessive deformations during sailing but leaving proper flexibility for trimming purposes. As a general rule, when the rig is fully loaded, the leeward shrouds should just begin to slacken. Diagonal shrouds pull the mast to windward in way of spreaders, which in turn push the mast to leeward due to shrouds compression, thus constituting a support for the mast. The mast's rake is controlled by tension of stays and mast bend by swept angle of spreaders. Pretension almost doubles mast compression and vertical shrouds tension.

Several variants of Skene's analytical approach are proposed in open literature. These are reviewed, among others, by Boote & Caponnetto (1991), Claughton et al. (1998), Marchaj (2000, 2003), Janssen (2004), Larsson & Eliasson (2007), Shenoi et al. (2009). Bruni (2007) summarizes the latest developments, including rules requirements that are in truth rather lacking. Safety factors, that are empirically derived and often impenetrable, account for uncertainties in strength assessment and loads definitions. The Nordic Boat Standard (NBS) that is practically recalled by Det Norske Veritas rules (DNV, 1983) and that is widely recognized as a robust design procedure for sail system of yachts, is applicable for normal masthead and fractional rigs but limited to 2 spreader pairs and medium size of the rig. Classification societies' rules generally provide simplified analytical scantling methods derived from NBS and applicable to relatively small boats, see e.g., Bureau Veritas rules (BV, 1993).

It is worth noting that inertial loads due to ship motions are not explicitly considered in analytical procedures, which are indeed fairly significant in large sail ships.

So far, factors of safety of 3.0 and more against breaking loads of components are primarily justified by uncertainties in the determination of actions and of their distribution on the rigging. Also, yachts and their rigs are becoming larger and larger, making weight and inertia effects more significant. Indeed, analytical procedures do not allow computing rig deformations under sailing. But this information is currently very important for sail design and for sailors.

Numerical methods

An alternative to current analytical approaches, nonlinear FE analyses, may be introduced considering cheaper and user-friendly FE software running on modern computation facilities. Germanisher Lloyd rules (GL, 2009) is the only class society to require such calculations in rules for mast and rigging.

Without any doubt, FE analyses are powerful tools for structural strength modelling, able to account for the nonlinear behaviour of rigs. However, their consistency heavily depends on structural idealization, which should be adequate for the limit state(s) considered and need correct definition of loading and boundary conditions. Different from analytical procedures, the strength properties of mast panels and standing rigging are designer-input to FE software as well as loads. However, in addition to forces and stresses, deformation of mast and rigging can be simulated.

Generally, strength properties are found iteratively until sufficient safety factors against defined limit states (e.g., global buckling) are reached. Analytical procedures are still useful for the first steps of the FE analysis.

According to GL, global buckling analysis of the rig, that is indeed the governing limit state, may be simulated using the Euler eigenmode method on FE models made by beam and truss elements. In short, eigenvalues of the stiffness matrix of the loaded/deformed structure are evaluated to obtain the buckling modes.

Yielding and collapse can be easily investigated under a number of different loading conditions, thus simulating several scenarios (e.g., various distributions of loads, inertial loads, accidental loads, etc.). Rather accurate rigs deformations are obtained, which are useful for sails design, mast tuning and sailing simulations.

Even made by 1-D elements, FE models are relatively complex due to nonlinearities: mast, boom and spreaders are simulated by beams; standing rigging needs to be simulated by trusses with null stiffness in compression, i.e., using nonlinear material elements; truss are also used for vang. Appropriate node connections should be defined, e.g., to simulate hinges between spreaders and mast tube. 1-D elements keep the model simpler for fast computations and easy changes in geometry and cross section properties, providing good global model results for buckling, yielding, deformations and collapse.

Models for local analyses have to be built up with shell, plate and/or brick elements (e.g., for halyards' holes or fittings). Local buckling, deformation and collapse in way of connections between components and tube shell are analysed. Sometimes mast tube panels, i.e. only the part of the mast between two spreader pairs, is modelled for local buckling analysis. Complete models including the whole mast tube are less frequent but are useful to consider local buckling in a global model.

A more advanced loads analysis is to include sails structural modeling in the calculation and to apply a pressure directly on sails. 2-D structural models (e.g., membranes) are then necessary, thus involving more complex numerical modeling.

The pressure distribution on the sail surfaces is transmitted to the rig through the fabric along the luff and the forestay. The sail's shape, while essential for aerodynamic analyses, has minimal influence on the mast loading once the sail is correctly linked to the rigs; rather its stiffness and resulting sag is important. Concentrated forces are also acting at the corners of the sails in halyards, outhaul and Cunningham. The halyard forces act twice on the sheave axles in top of the mast. If sails are modelled, battens and tracks on luff can also be properly simulated.

The wind pressure on sail may be realistically distributed according to wing profile theory and, eventually, a fluid structure interaction (FSI) numerical model can be set in order to find the sails' equilibrium shape in wind flow. Indeed, this latter option is still a matter for researchers and well-funded racing teams. In spite of the latest developments, there are limitations in accuracy and in the size of CFD computations, especially for downwind courses; also, structural input data are often rather uncertain.

Test case applications

Test case description

The yacht selected as the test case is a very typical one, recently launched on the market. She is a cruiser-racer, 45' in length. The main dimensions are reported in Table 1.

Table 1: Test case yacht main dimensions

Overall length	13.95m
Hull length:	13.60m
Waterline length:	12.16m
Hull width:	4.30m
Displacement:	10.640kg
Draft:	2.30m
Keel weight:	3.100kg
Mainsail area	63.0m^2
Foresail area	50.2m^2
Chain-plate width	2.682m

Mast, spreaders, and boom are made by aluminium alloy extruded profiles and rigging is made by 'Dyform' steel wires of appropriate diameters, according to mast and rigging manufacturer's recommendation (Sparcraft, 2010). The sail plan is shown in Fig. 4. Sails were specifically designed for this yacht and are rather complex fabrics realized with two polyester films in which aramid fibers are included; polyester taffeta are the external protective layers. Construction details are confidential.

Analytical calculations

Righting moment (RM) at safety working angle (SWA) is the main input of analytical procedures. Indeed, the actual value of RM is difficult to obtain in practice, especially in the design phase. SWA is assumed between 25° and 30°. In general, mast designers know the actual stability at 1° heel angle, the value is multiplied by the SWA assuming linear the first part of the stability diagram, thus overestimating the $RM_{30°}$.

Approximate methods to estimate RM are available like the one proposed by Gerritsma et al. (1993), the one reported by Larsson and Eliasson (2007) and the one reported in BV rules (1993).

For the test case, a value of about $RM_{30°} \approx 120$kNm was conservatively estimated using the above-mentioned methods and verified by an inclining test. However, such a value is subject to large uncertainties and it is a design reference value only.

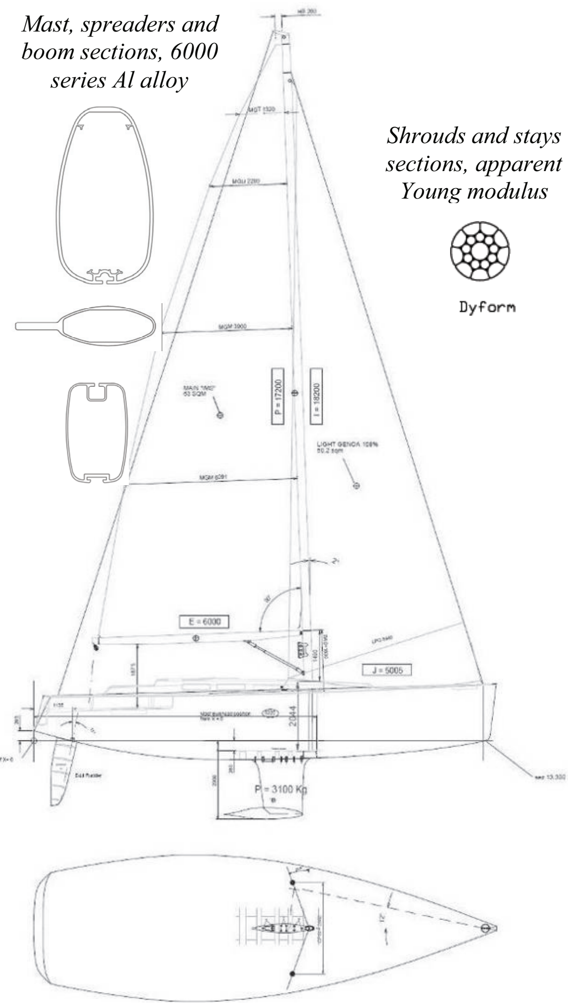

Fig. 4: Sail Plan of Selected Test Case (D45 Performance)

The Skene's method allows evaluating the compressive load on the mast and the minimum mast inertia based on the Euler column buckling theory. Actually, implicit formulations and inexplicable coefficients are provided in the traditional check for the assessment of minimum mast inertia (see Kinney, 1962). Janssen (2004) discloses fundamentals by comparing Skene's formulae and Euler's theory, finally resulting in Eq.s 1. Transverse and longitudinal buckling, different support lengths and boundary conditions may then be examined.

$$P = 1.85\frac{1.5 GZ_{30^\circ}\cdot\Delta\cdot g}{b/2} = 1.85\frac{1.5\cdot RM_{30^\circ}}{b/2}; P_{cr} = \frac{\pi^2 EI}{k^2L^2} \quad (1)$$

Where:

P=mast compression force [N]

Δ= weight displacement [kg]

g=gravity acceleration [m/s^2]

b=chain plate width [m]

GZ_{30°=righting moment arm at 30° heel [m]

1.5=coefficient accounting heeling greater than 30°

1.85=coefficient for stays, sheeting and halyard loads

P_{cr}=Euler buckling load for panel [N]

E=Young modulus in axial direction of the panel [Pa]

I=long. or transv. inertia of cross section [m^4]

L=length of panel between supports [m]

k=support factor depending on boundary conditions

The lowest mast panel, whose length is about 5m, is the most critical one. Both transversal and longitudinal inertia (I_{xx}=844cm^4, I_{yy}=2638cm^4) of the lowest mast panel are just verified taking into account the boundary conditions (k<1). An important point is that the Euler buckling method is a linear representation of a nonlinear phenomenon. The formula is a theoretical approach of buckling for ideal undisturbed structures under a pure compression force. Longitudinal bending of mast, induced e.g. by swept spreaders, backstay and sail loads, is not explicitly accounted for. The resulting bending stiffness heavily depends on the type of support, expressed in the k factor, ranging from 0.5 (clamped at one end, support without rotation at the other end) to 2 (clamped at one end only), i.e., on actual arrangement of mast step and of spreader connections.

Rigging is evaluated as a statically determined structure sustaining the heeling forces from sails applied at hinges between mast and spreaders. Rod and spreaders cross section areas of the yacht satisfy the yielding limit state, even considering a safety factor larger than 2.5. With this approach, it is not possible to examine, for example, collapse, local buckling or mast tuning effects, interactions due to aft swept spreaders, stays, jumpers, etc. It is also not possible to determine the general behaviour of a rig, for example, bending and deformation under normal sailing situations. Even the pretension is not explicitly considered or the longitudinal strength as loading is only transversal.

Finite element models

Various FE analyses were carried out with the aim to explore the possibilities offered by numerical calculations rather than to obtain results for a specific design. Thus, increasingly complex FE models were built and results critically reviewed to assess whether the procedure is cost-effective for the current design practice. It may happen, in fact, that too complex modelling is useless if not counterproductive because of the lack of correct input data. As a matter of fact, structural idealization should account for limit state to assess and available input data and due attention should be paid, especially in defining loading and boundary conditions.

Generally, FE models end at the connections to the hull. The hull is not explicitly modelled, limiting the model size, but its bending stiffness may be simulated by appropriate springs at stays' and mast's ends, if necessary.

The mast tube can be modelled with beam elements representing only a line at the neutral axis. Spreaders and stays may be connected to the mast by rigid links, transferring degrees of freedom (DOF) from the neutral axis of mast to actual attachment of spreaders. The same procedure may be used for goose neck, stays, internal reinforcements of mast tube, etc. Fig. 5 shows a 1-D model built in the ADINA (2009) environment.

Pretension of mast tuning can either be applied as initial strains of truss elements representing shrouds and stays, also necessary for loaded nonlinear trusses to avoid singular stiffness matrix, or by simulating the mast jack normally used for large yachts to push up the mast step during dock tuning. In both modes, pretension is applied stepwise in a long procedure looking at mast and spreaders deflection and at shrouds' and stays' stresses under loading. Numerical simulations help technicians before and during the work. It is worth noting that pretensions in the shrouds are not absolutely symmetrical in reality, e.g., because the turnbuckles only allow turn angles of 180° for the securing by cotter pins. This is likely neglected in numerical models (Graβe, 2002).

shows buckling modes of the loaded structure, using linearized buckling as required by GL. It is worth noting that rule-calculated forces should equilibrate the RM, but this is not guaranteed for mast with three or more spreaders' pairs as only two equilibrium equations are available to define forces; then, more than one distribution is possible.

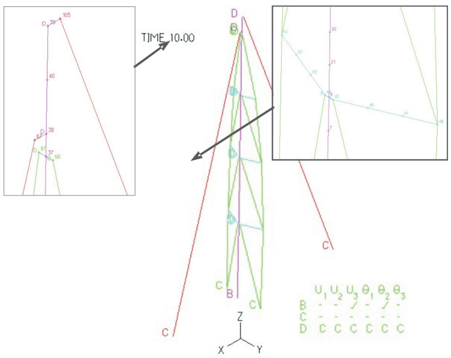

Fig. 5: 1-D Mast Model with Rigid Links

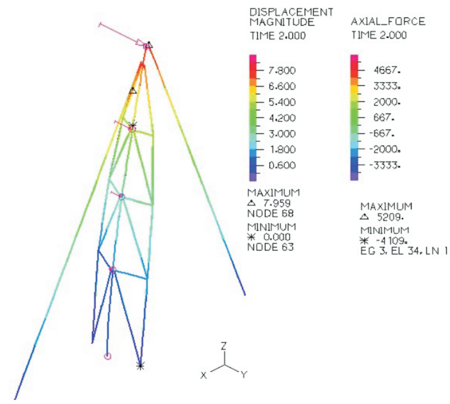

Fig. 6: No Pretension Load Applied, max displ. ≈ 8.0m

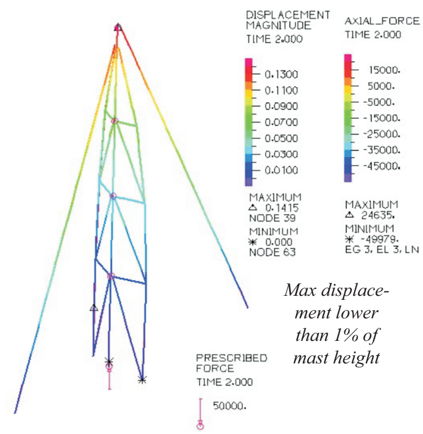

Fig. 7: 50KN Pretension Load Applied, max displ. ≈0.14m

Transversal loads on mast are applied as concentrated forces at spreader attachments or distributed with triangular, trapezoidal, elliptical, or different laws along the mast (see e.g. Claughton et al., 1998). Inertia loads can be considered by setting densities and accelerations, including gravity, to apply mass proportional loads; this is an option available in most FE software that allows accounting for dynamic loads in a quasi-static mode.

Spreaders may be either hinged or fixed at mast. Investigation about this option is rather easy in 1-D models if rotational DOF are disconnected at spreader ends, indeed simplifying even more the FE model by deleting equations relevant to rotational DOF.

The forestay is typically simulated with one nonlinear truss element in the same way of shrouds and back stay, if no loads from foresail are applied along the luff; concentrated forces should be applied on mast simulating the stay effects on it. Alternatively, to get the influence of the forestay sag due to sail load, several trusses are placed and forces need to be applied on end nodes of each truss to avoid singular stiffness matrix. Beams elements could only be used in rare cases when bending stiffness of the stay is significant, i.e., the stay is not a cable because of its real features; then, distributed loads can be applied on elements; nonlinear material used to account for null compressive stiffness cannot generally be associated with this element type.

In the following Figures 6-9, examples of different FE analyses carried out using 1-D nonlinear models are reported, considering forces applied at spreader ends to equilibrate the RM. Fig. 6-7 refer to lateral forces estimated according to GL rules. Fig. 8

Fig. 9 refers to a grounding, causing a 2g forward acceleration plus a 0.175rad/s^2 pitch angular acceleration during sailing (speed: ≈8kt, time to stop: ≈0.25s). It is noted that this rather extreme loading is critical due to large displacement, though the light weight of structure.

When collapse analysis is carried out, plasticization of material should be considered. Actually, beam elements of general cross sections cannot consider the development of plastic hinges. Then, shell elements are used to build the mast tube as shown in Fig. 10. Such FE models are also useful to assess local buckling of mast tube. Beam elements of simplified cross section (T, or rectangular) may be used to account for internal stiffeners and luff track inside the tube. Fig. 11 also shows the modelling of the boom. Its connection at goose-neck requires transferring only translational DOF and forces. A possible modelling solution is shown in Fig. 12, where rigid links account for the stiff collar of the mast in way of boom attachment. A similar solution can be adopted for spreaders and other shell-modelled rig components.

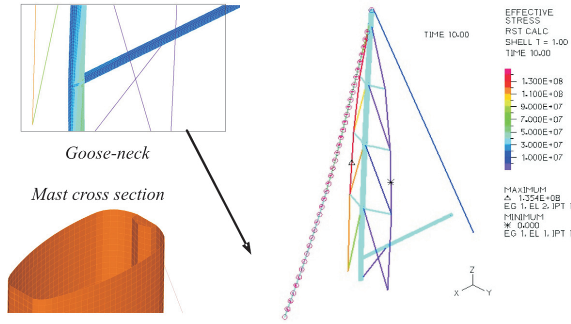

Fig. 11: Mast Tube and Boom, 2-D Model

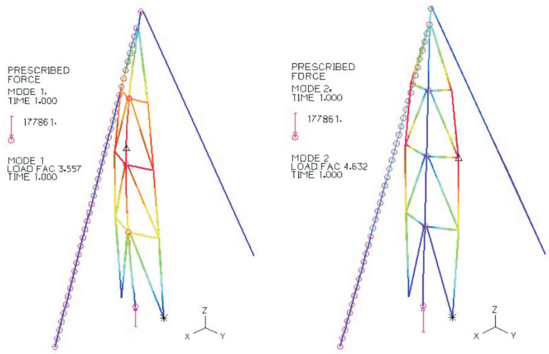

Fig. 8: 50KN Pretension & Loads Applied, Euler eigenvalues

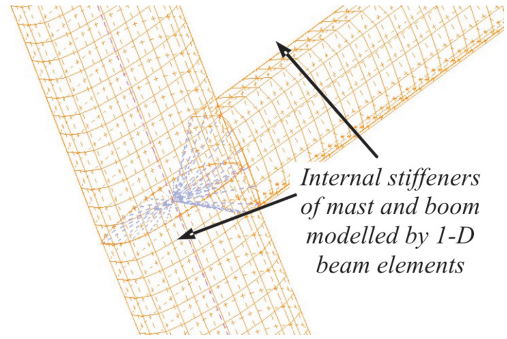

Fig. 12: Boom Connection at Goose-Neck

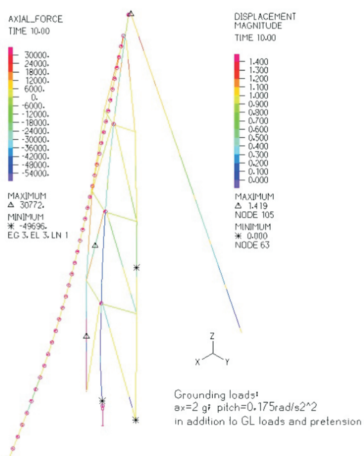

Fig. 9: Grounding Load under Sailing Conditions

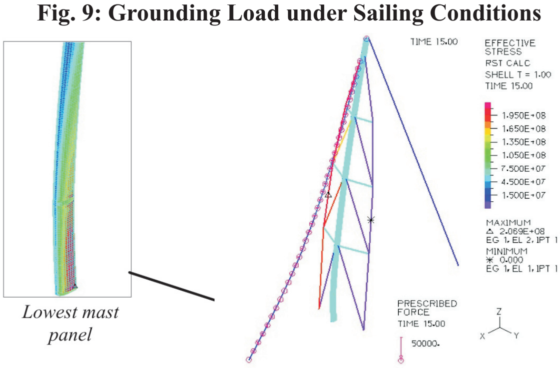

Fig. 10: 2-D Model of Mast Tube

Few papers dealing with the modelling of the structural behaviour of sails are found in open literature. However, recently introduced laminated sailcloth changed the world of sail-making. In general, shell structural problems fall into one of the categories of membrane-dominated, bending-dominated or mixed. In some problems, there is no convergence and shells are unduly sensitive in their behavior because the ratio of membrane to bending stored energy changes significantly, indeed fluctuating with changes in shell thickness (Bathe et al., 2003). Sails are a typical example of such sensitive structures and previous works faced the problem based on a membrane model or sometimes on a 'cables net' model.

The 'cables net' model is very representative for the weft/warp directions but it cannot catch the redistribution of stress/strain due to yarns weaving. This model takes into account the sail unilateral behaviour, ensuring the approach of a two-dimensional structure without thickness (a sail) using a set of mono-dimensional structures (cables). On the other hand, a membrane model of extremely thin fabric causes numerical instabilities and needs proper pretension (Spalatelu-Lazar et al., 2008).

Recently, Trimarchi and Rizzo (2009) reviewed problems in structural modelling of sail membranes from basic principles. Indeed, the CST (Constant Strain Triangle) element they implemented in the software is very dangerous in the hands of inexperienced users. However, they calibrated their calculation with experimental testing that is still continuing in the Ship Structures Lab of the Genova University, aimed at setting a dedicated standard for the characterization of sail properties.

Fig. 13 shows the deformation of the sails of the test case assuming orthotropic material and 3-D membrane (plane stress) elements; this may be sufficient for a Dacron sail provided that Young modulus and Poisson ratio are well calibrated and the analysis is aimed at obtaining a global view of the deformed shape and estimates of loads to be transferred on the mast model. Seams were modelled by trusses on sails' edges, stabilizing the calculation. Assuming 10με initial strains on all elements and increasing pressure slowly (first step is 10^{-5} of total load), convergence is obtained. A wrinkling model is implemented, reducing element stiffness in principal directions by 10^6 if negative principal stresses occur. It is worth noting that even a simplified membrane model is rather challenging to run; detailed simulation of battens, internal seams, fittings, etc. may help convergence only if correctly implemented.

Pressure: 48MPa
Thickness: 0.32mm
Young modulus: 1700MPa
Poisson ratio: 0.33

All sail edges are free except mainsail luff on mast that is fixed.

Forestay and edge seams of sails modelled.

Clew, tack and head are fixed.

Reactions equilibrate the pressure load on the sails.

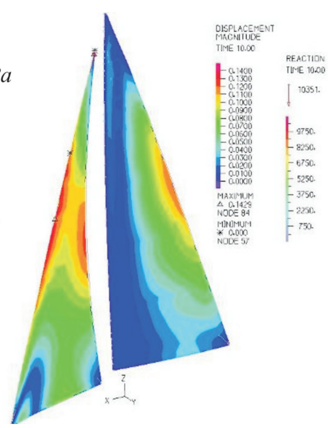

Fig. 13: Deformation of Dacron Sails (membrane elem.)

If shell elements are used in lieu of membranes in the same FE model, rather different results are obtained, as shown in Fig. 14, due to bending stiffness. Actually, deformation energy is split among more DOF. The advantage is that shell elements do not need wrinkling models as they naturally catch the phenomenon. The trick is still in the correct modelling and characterization of sail materials.

Same FE model as Fig. 13 but elements switched to 4 nodes isoparametric shell and material to isotropic elastic.

Rather different displacement field and values w.r.t. membrane model is found.

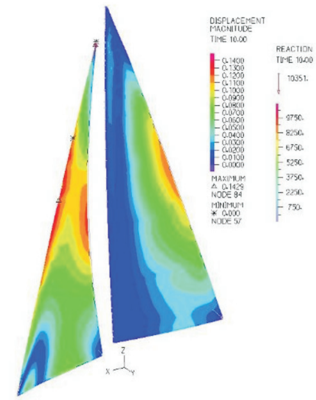

Fig. 14: Deformation of Dacron Sails (shell element)

For a detailed analysis of the sail behaviour, accounting for its strength, seams and battens can be included. Rather than woven materials that are fairly well simulated by membrane models, modern racing sails are quasi-membranes as they incorporate fibres, properly oriented to form a net, sandwiched in two laminated film; a light woven material like taffeta is sometimes added on external faces for protective purposes. Recent fabrication techniques allow placing fibres along curvilinear paths, thus providing one-piece sails. The structural analysis of such types of structures is not straightforward. In principle, membranes and orthotropic materials are adequate but this strategy implies the definition of material axes, which is not easy for curvilinear fibre reinforced sails. On the other hand, the 'cable net' model could be the right choice as the stiffness direction is naturally assured.

Conclusions

A review of the structural assessment methods for sail systems is presented. While analytical procedures are still the first step of the design, numerical analyses are to a greater extent carried out for different purposes.

Global deformations are important results of nonlinear FE computations, helping in mast tuning and in design of sails. Actually, apart from traditional limit states assessed for safety reasons (i.e. collapse), calculations are carried out for optimization purposes, e.g., estimates of global and local deformations of mast and rigging that dramatically affect sailing performances. Moreover, interaction of compression and bending behavior of masts, which is crucial in the assessment of buckling collapse, can be accounted for.

Table 2 shows the limit states normally defined for mast and rigging in connection to FE idealizations: 1-D models are built by truss and beam elements, 2-D models by shell elements, 3-D models include solid elements for specific components and are generally partial models. Global models simulate the mast and rigging as a whole, including the sails if transmitted loads are not separately evaluated and applied. Local models are convenient for detailed analyses of individual components, e.g., mast tube panels. Partial modeling is sometimes sufficient but, on occasion, it is convenient to consider all the structure for local modeling (e.g., detailed modeling of mast-spreader connections to account for their effect on progressive buckling of the mast tube).

Table 2: Limit states and structural idealization of rigs

Limit state	FE modeling		
	1-D	2-D	2-D + 3-D
Buckling	global	local	-
Yielding	-	global	fittings / mast step
Collapse	global	local	
Deformation	global	local	-
Accidental	global	-	-
Fatigue	-	-	fittings/welds

Modeling of sails is really a challenge and the coupling of sail models with mast and rigging ones is time-consuming and appropriate skills and computation facilities are necessary, especially for FSI analyses on a model considering mast, rigging and sails. Therefore, the aerodynamic simulations are often carried out on sails separately and assumed as rigid bodies, then calculated pressure distribution is applied on the structural model of sails only and in turn to the one of mast and rigging. While analytical approaches along with 1-D nonlinear FE are sufficient for design limit states, it may be not for performance analyses where deformations and dynamic behavior of the structure needs to be predicted in detail.

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