Scantling of sailing yacht mast and sail deformation simulation using Finite Elements.

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Master Thesis

presented in partial fulfillment
of the requirements for the double degree:
“Advanced Master in Naval Architecture” conferred by University of Liege
"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics, Energetics and Propulsion” conferred by Ecole Centrale de Nantes

developed at University of Genoa
in the framework of the

“EMSHIP”
Erasmus Mundus Master Course
in “Integrated Advanced Ship Design”

Ref. 159652-1-2009-1-BE-ERA MUNDUS-EMMC

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La Spezia, February 2012

CONTENTS

Abstract

When developing a sailing boat, the design and scantling of the rigging system supporting the sails is often a critical part of the project. Those rigging systems (mast and standing rigging) are composed of cables and beams subjected to high compression loads and large deformations.

One of the most difficult tasks for a rig designer is to estimate the maximum loading condition for a rig. These loads determine the mast tube dimensions such as wall thickness and the stay diameters. As a consequence, the loads basically determine the total weight of a rig. The constant drive for better sailing performance pushes the design to the limits, even for cruising yachts.

Standard approaches to define loads for a rig start with the righting moment of a yacht of heel. In rig dimensioning procedures it is a common practice to take the righting moment of the sailing yacht at 30 degrees as a base to compute the compression forces in the mast tube and the tension forces in the standing rigging.

With FEA performed on yacht rigs it is possible to determine the efforts in all parts of the rig and to predict deformations of the mast and the standing rigging.

A load model based on sail areas for application in FEA is developed. The tool consists of a force prediction model, estimating the external forces acting on the rig during sailing. Subsequently these forces are used in a finite element analyses to determine the structural behavior of the rig. In several analyses steps the rig can be optimized. Due to the generic set up of the tool, different rig configurations can easily be compared.

But defining loads on the rig for FEA is still a big problem. Without the right loads even the best simulation of the rig structure is worthless. There are many different loads on a sailing rig. Pretension, also referred to as “dock tuning”, is one load case. Sail loads as a function of wind velocity, apparent wind angle and sail combinations are a second case. A third case is inertial forces when the yacht is moving with all six degrees of freedom and big accelerations in waves (e.g. a rapid deceleration when nose diving). A fourth case is the weight of the rig itself which has to be considered with large rigs.

Finally, conclusions and recommendations are presented, as well as suggestions about future work related to the project.

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CHAP. 1 INTRODUCTION

Mast and rig are essential parts in sail yachts. They support the sails which are basically the engine of the boat. Performance and safety of a sailing yacht depend on a great extent on its mast and rigging design. Any mast failure can have dramatic consequences for both the boat and its crew.

To optimize the stability of the boat and its sailing performances in navigation the system must be as light as possible and should have a vertical center of gravity as low as possible.

Decreasing mast weight and lowering its centre of gravity will also impact the dynamic behaviour of the boat by reducing pitch and roll movement with a considerable increase in boat performance and comfort.

The rigging and the mast have also to be optimized in order to reduce windage and to disturb as little as possible the incoming flow arriving on the sails.

As the sails are physically linked to the mast, its shape and behavior will have an influence the shape of the sails. This is a second function of the rig: the mast as to be able to bend in a certain extent to adapt its shape and change the shape of the sails and thus modifying the power developed by the sails in order to match the sailing conditions.

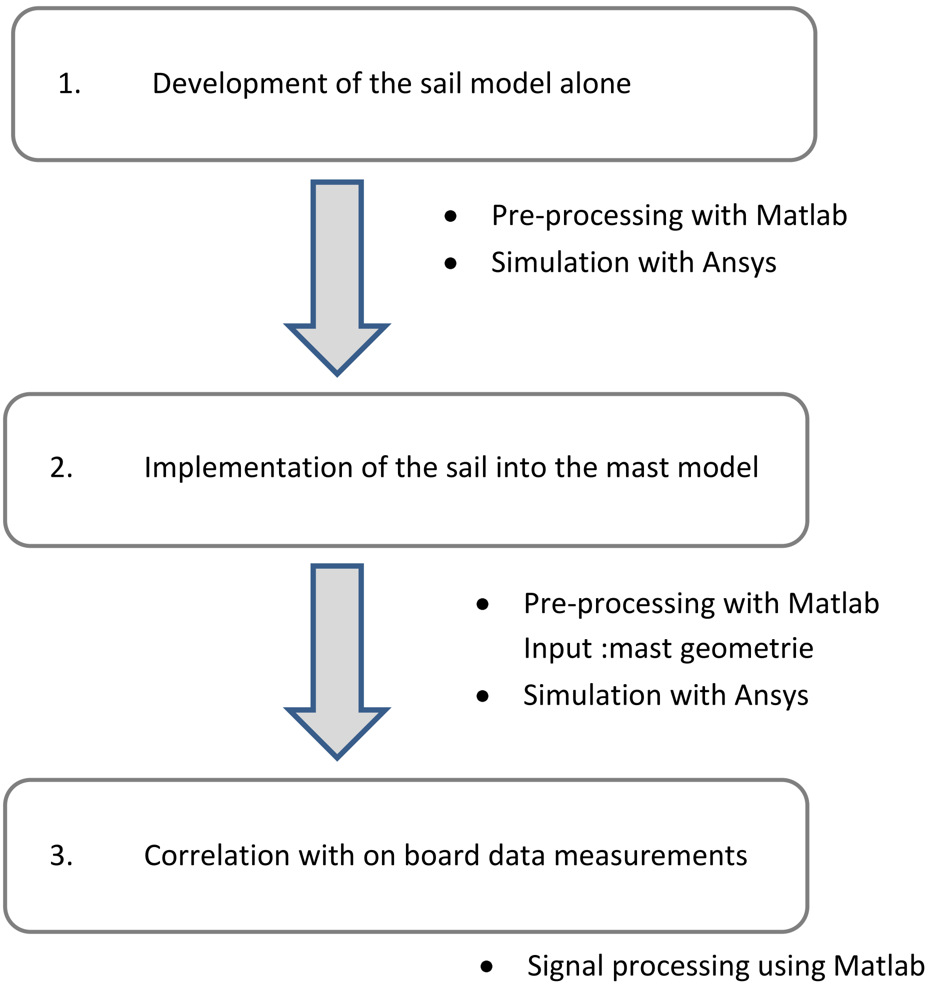
From a mechanical point of view, masts are complexes systems with high aspect ratio (a mast is basically a high slender column). They are subjected to high compression forces leading to possible instability problems. In addition the applied loads are uncertain, difficult to measure and subjected to high variation according to the sailing conditions and sea state.

Mast scantling in usually performed using empirical formulas. This way of proceeding is valid for small sailing boat. For super sailing yachts and racing yachts, more advanced analysis need to be performed. Finite element method is then needed to get accurate results.

With a Finite Element Analysis three dimensional nature of rigging geometry can be taken into account as well as a more complex load distribution. But more important is the possibility to take large displacement of the structure and its nonlinear behavior.

The aim of this thesis is to develop a simple but yet accurate way to predict the loads created by sails for mast scantling purposes.

The chosen way was to directly integrate 3D model of a sail in an existing finite element model of a mast and to run simulations while applying pressure (or equivalent load) to the sail.



CHAP 2 SAIL BOAT: OVERVIEW

1. PHYSICS OF SAILING BOAT

A sail boat is a complex machine getting more and more sophisticated as research and development goes on. This complexity comes from the fact that a sailing boat is a physical system interacting simultaneously in two different fluids: air and water.

The sails, which are the airborne part of the sailing boat, create a force by deviating the air flow (wind) from its original trajectory. This force constitutes the propulsion of the sailboat.

Water will support the boat generating Archimedean force (or if the boat is fast enough, the hull will generate a lift, in that case the boat is planning).

If the wind conditions do not allow generating a force in the direction of the desired course, a waterborne component called keel will almost eliminate the sidewise slippage. The boat can move only in the direction of the keel, which is also the direction of her center line.

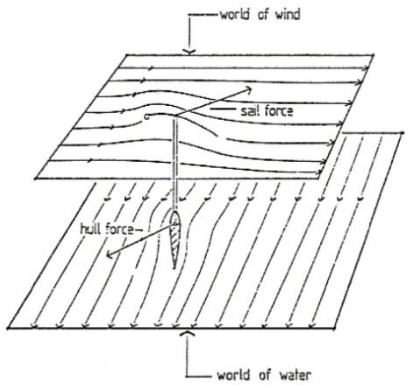


Figure 1 Principle of equilibrium between aero and hydro forces

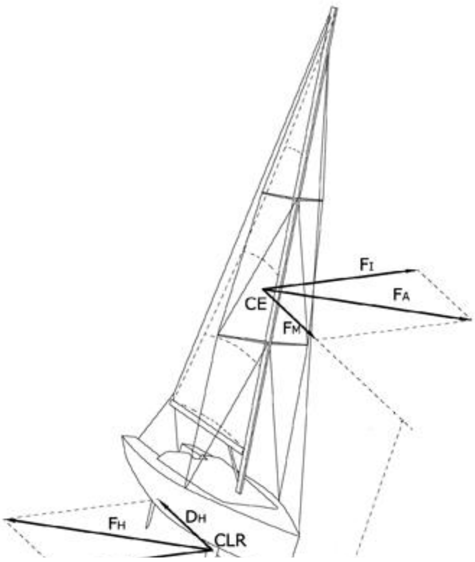


Figure 2 Sail boat equilibrium

Force equilibrium then is being established between the aerodynamic and hydrodynamic forces. Whenever the total wind-generated force points forwards with respect to the keel, the boat moves forwards, in the direction of its keel.

The moment created by the weight and buoyancy (righting moment) balances the previous moment and leads to the full equilibrium.

2. MAST AND RIGGING OVERVIEW

If the sails system has the fundamental function of transforming the wind velocity in propulsive force for the vessel, spars and rigs has the equally important task of supporting the sail and controlling the optimum sail shape.

2.1 Terminology

2.1.1 Mast

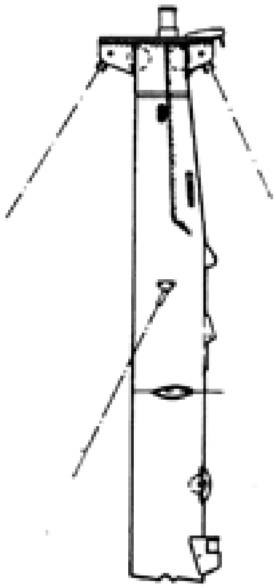
When talking about the mast we usually refer to the entire rigging system.

Several considerations have to be taken into account when designing the mast section. From an aerodynamic point of view, the mast will induce a detachment zone (bubble detachment) on the extrados, close to the leading edge of the mainsail with the consequence of reducing the sail efficiency. In that intention the section shape has to minimise the mast projected area

The other aspect to be taken into account deals with the mechanical requirements. Mast are getting higher and lateral support is increasing more than longitudinal support. (higher number of spreaders but also longer spreader

In addition it is to point out that the requirements for higher sailing yachts performances has led to higher aspect ratio of rigs and, as a consequence, the demand of longitudinal inertia is even more greater than the transverse one. An imperative requirement for a mast section is then to provide adequate inertia with minimum dimensions in order to assure good buckling resistance and to avoid as much as possible any interaction with the mainsail.

The tapering (reduction of the section) helps reducing the weight of the mast tube in the upper part. It also gives flexibility to the top part of the mast which can be useful for mainsail trimming purposes.



2.1.2 Stays

Even if many kinds of small sailing boats are fitted with unstayed masts, for others sailing yachts the mast should be sustained by a three-dimensional rigging system. athwartship (shrouds) and in the fore and aft plane (stays).

Rigs are attached to the mast at different levels and secured to the yacht hull; the shrouds are secured to the hull by chainplates and the stays are connected to reinforced hull points in correspondence of the bow (headstay) and of the stern (backstay).

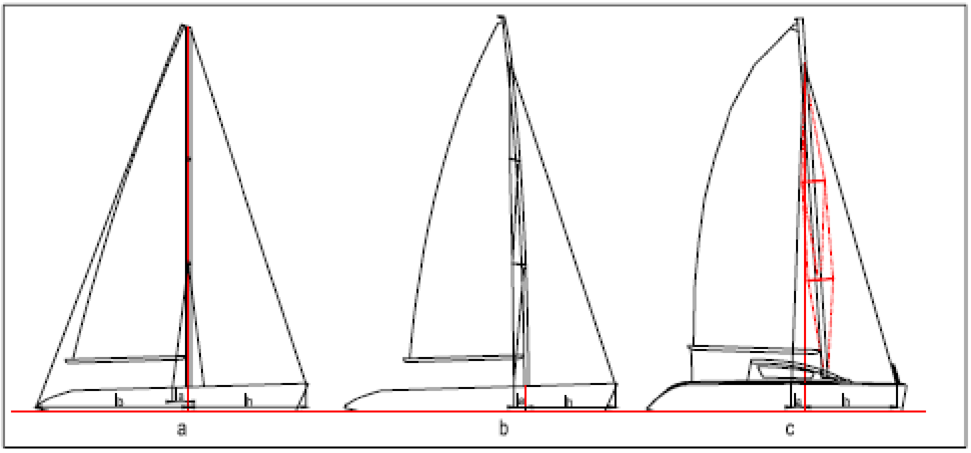


Figure 3 Longitudinal rig arrangements (source ISO 112215-9)

Shrouds can be continuous or discontinuous; the continuous solution consists of full-length shrouds, with constant section, from the mast attachment point down to the chain plates. The discontinuous solution consists in separate spans from two sets of spreaders connected at the spreader end with mechanic links.

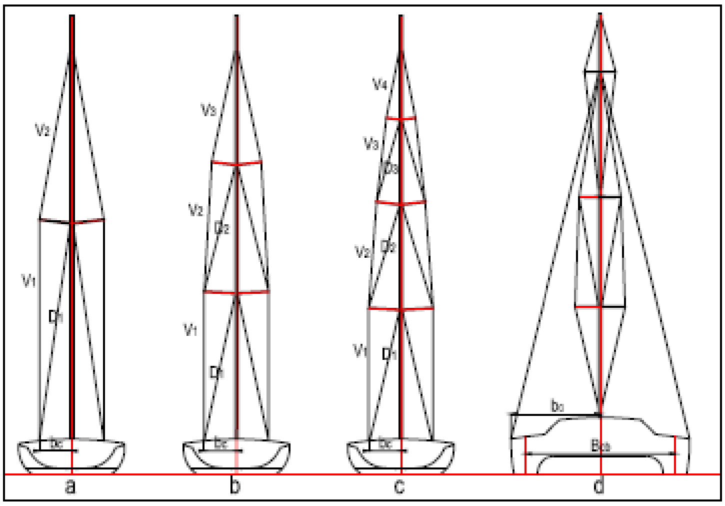


Figure 4 Transversal rig arrangements (source ISO 112215-9)

2.1.3 spreaders

To avoid long unsupported spans that may cause buckling phenomena, masts are fitted with spreaders, in a number to keep the shroud angle over 10°.

A spreader is a spar used to deflect the shrouds to allow them to better support the mast. By increasing the angle between the mast and the shrouds they reduce the compression due to those elements

Spreaders are mainly loaded in pure compression transmitted by the shroud tension; in addition mast bending can cause also induce spreader bending in the horizontal plane.

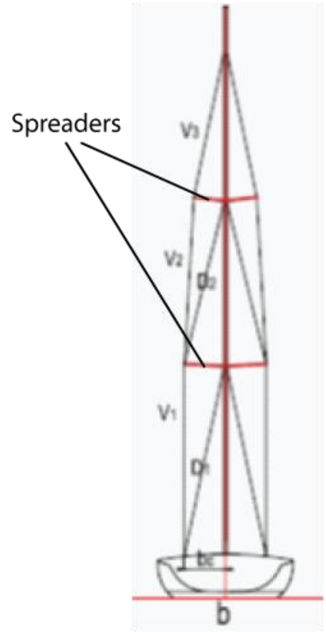


Figure 5 Tranversal rigging, two spreaders configuration.

2.1.4 Boom and vang

In sailing, a boom is a pole, along the foot of a sail, which improves control of the trimming angle and shape of the sail. The primary action of the boom is to keep the foot of the sail flatter when the sail angle is away from the centerline of the boat. The boom also serves as an attachment point for additional control lines.

A boom vang is a line or piston system on a sailboat used to exert downward force on the boom and thus control the shape of the sail.

3. MATERIAL

3.1 mast

3.1.1 Aluminum

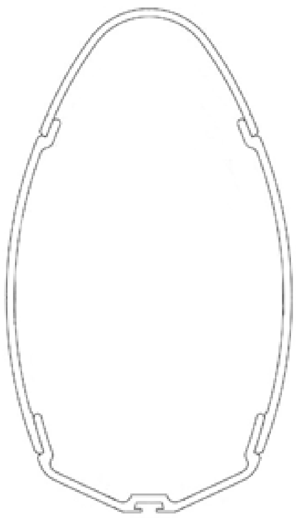
Traditionally spars were made out of wood (mainly conifer). Since the 1960's wood had been replaced by aluminum due to its greater durability, higher specific properties and lower cost. Aluminum alloys of 6000 series are the most commonly used. These series of aluminium alloys have high mechanic characteristics but also good resistance to marine environment corrosion.

For short, economical masts, 6063 alloy is used, 6061 type is for high quality masts and 6082 type, which is the most expensive one, for racing yacht masts.

The wide majority of aluminium masts are extruded, with a constant section and a tapering on the top section.

It is also common practice, in the case of big and/or high performance yachts, to reinforce the mast base and additional parts subjected to high stress (Boom attachment for instance). This is performed by bolting additional aluminium plates inside the mast.

The length of extruded mast section is usually limited to a maximum of 18m. For longer mast it is necessary to proceed to a junction. This type of junction is also realized by bolding the two sections together using inner aluminium plates.



Aluminium masts fitting maxi sailing yacht are usually too big to be extruded. In addition they are usually one-off units which would make the manufacturing of a extrusion die to expensive. Therefore they require being build out of panels welded together leading to a complex design and building process.

3.1.2 Carbon fiber

Carbon masts began to be used in the early 1980's, initially for racing dinghies, then in the America's Cup and finally spreading to other racing yachts. Nowadays carbon fiber spars are quite common but keep being considered when weight is critical and are therefore limited to racing yachts or performance oriented cruising yachts.

These spars are much stiffer, stronger and more tolerant than their aluminium equivalent while significantly reducing weight aloft and improving stability.

Through laminate optimization and material selection it is possible to finely tune the mast stiffness and deflection profiles to suit the sails shape and reach a better aerodynamic efficiency.

Dimensioning of composite masts is complex and requires analysis of global and local buckling, evaluation of the strength reduction due to many attachments and geometrical variations. Carbon masts consist mainly of longitudinal unidirectional fibers (over 80%) with some at ±45° and 90°.The matrix used are epoxy resins.

Mast of important dimensions, (like the one fitting maxi sailing yacht) are manufactured in two half shells. Pre-impregnated fibers are laid up in a female mold before being cured at 120°C in an autoclave. Reinforcement for hardware attachment points are laid up during the same staking sequence. The two parts are then bonded together.

Alternative fabrication process involving fiber braiding around a male mandrel produces a single part mast. This type of process is very well suited for industrial production.

A large number of finishing operations are then required, including machining of holes to fix the mainsail track, rigging attachments and spreader features.

3.2 stays

Today the wide majority of production sail boat is fitted with standing rigging composed by steel wire rope.

For racing yachts and super yachts instead of using steel wire rope, the standing rigging is composed of massive steel rods. Nitronic 50 is one of the most widely used steel alloys for this kind of application. Nitronic 50 is an austenitic, nitrogen strengthened steel providing a combination of high corrosion resistance and structural properties approximately twice the yield strength of comparable commercial metals such as 316 and 316L stainless steel.

Standing rigging has also seen considerable evolutions in recent years as steel is being replaced by high performance synthetic fibers, as PBO and aramid. The use of continuous fiber slings results in lighter cables. The last developments are about carbon fiber rigging.

3.3 Keel stepped/deck stepped mast.

Masts can be either deck-stepped or keel stepped. For large sailing yachts keel stepped mast is preferable, mainly for its higher resistance with regard to bending, compression and buckling. This is due to the higher efficiency of the lower end constraint and to the contribution of the through-deck passage, which can be considered an additional constraint.

CHAP 3 RIGGING SYSTEMS

1. MAST AND RIGGING REQUIREMENTS

As mentioned in chapter 1 the main function of the mast is to support the sails. Excessive rig deformation, allowed by non-sufficient system stiffness, has the negative effect of changing the shape of the sails, decreasing the propulsive efficiency of the boat. On the other hand a certain amount of flexibility is necessary to allow the mast to be bended in order to be able to change the shape of the sail according to the sailing conditions. As a consequence, mast and rigging should have “reasonably resistant” section.

2. RIGGING LOADING CONDITIONS

2.1 Rig mechanic, interaction with sails

A sail is behaving like a membrane that would be attached on 3 points (see Figure 7). The loads developed by the sail are transmitted to the mast through those 3 points. When the sail is contrain by the mast, for in instance for the case of the main sail, forces are tranmited along the heigh of the mast.(see Figure 6).

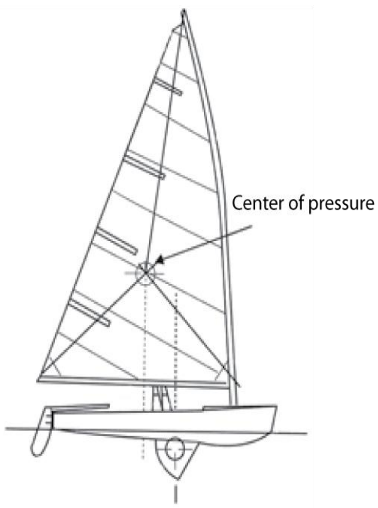


Figure 7 Equivalence between sail and a three cable net

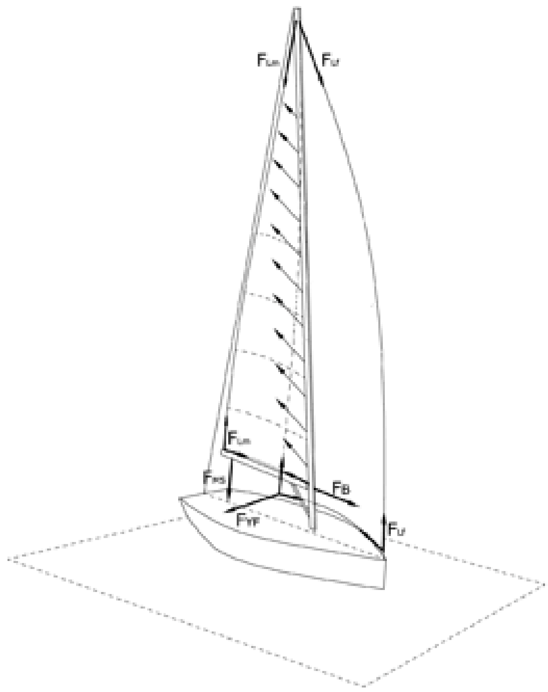


Figure 6 Loads applied on the mast by the sail (Bruni 2007)

3. MASTS MECHANIC

3.1.1 mast

The mast and its rigs are formed of spars: mast and spreaders that can bear flexion (thanks to their inertia) and tension, compression tension.

A mast step is subjected to compression and shear forces. Especially for keel-stepped masts, shear is mainly generated by boom compression.

Mast can be stepped in two different ways: on the deck or stepped on the keel (passing through the deck).

On the deck the mast is stepped on metal support, hinged by a pivot bolt and blocked by a security retaining pin. The support has also the function of distributing the mast compression over a wide deck area. It is also necessary to insert a pillar beneath the deck in order to transfer the compression to bottom structure or, when possible, to reinforce the section with a rigid bulkhead.

The solution of stepping the mast on the deck does not require any opening in the deck eliminating any possibilities of water entrance. In addition event thought a pillar is required under the deck for structural purpose, the space below deck is more important.

The keel stepped solution is, from structural point of view, better. Especially for large cruising yachts where high compressive stresses occurs. The main drawback of this configuration is the important space occupied by the mast below deck, raising problems for cabin layout. The opening to let the mast cross the deck can let water leak inside the hull.

A keel stepped mast is supported by hull structures, on a longitudinal stiffener which distributes the compression over several hull frames. In GRP boats the mast is stepped on thick aluminium or stainless steel plate. The opening in the deck is reinforced by transverse beams and local longitudinal stiffeners. The mast is kept in position by wood or plastic chocks. On modern super yachts the opening is sealed using a special resin which has a double function of blocking the mast and making the opening waterproof.

As mentioned before, the keel-stepped mast is more efficiently constrained at its lower end.

Masts can be either deck-stepped or keel stepped. For large sailing yachts keel stepped mast is preferable, mainly for its higher resistance with regard to bending, compression and buckling. This is due to the higher efficiency of the lower end constraint and to the contribution of the through-deck passage, which can be considered an additional constraint.

The passage through the deck can be considered an additional constraint which absorbs a part of compression. This consideration allows reducing the section and wires dimensions saving weight and windage or, as an alternative, to increase the panel span.

The keel-stepped solution allows using hydraulic mast jack to put the rig into compression.

Regarding deck stepped mast, the lower panel, which is affected by the higher compression, behaves like a beam column pin jointed at each end. This fact lower the critical load so a larger mast section should be adopted with, if possible, wider lower shrouds than what would be advisable. It can be said that stepping masts on deck is more difficult and expensive and it results in a larger mast section with respect to the keel-stepped solution.

The use of sweep spreader has the advantage of forcing the mast tube to bend. The spreaders push the mast forward and in response the mast put the spreaders into compression. This leads to a very stable equilibrium and brings to the mast some longitudinal support that is not possible to have with no swept spreaders.

The consequence of this bending is to add some additional compression on the back face of the mast increasing the resulting stress.

The section shape of the mast has be design tacking into account this additional stress.

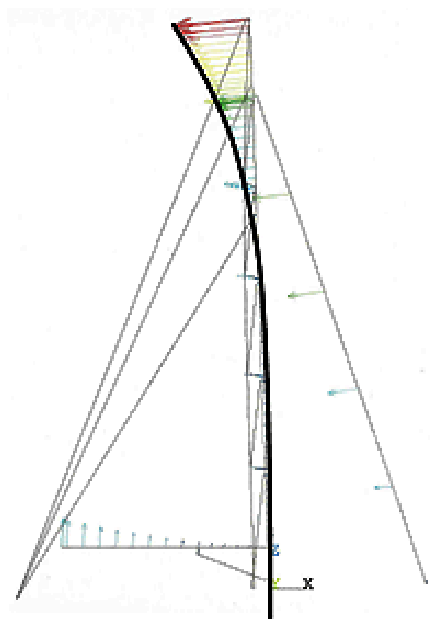


Figure 8 View of a bended mast

3.1.2 Response of the mast tube : global and local buckling.

The mast tube is mainly subjected to compression. In addition a mast tube can be considered as a slender column meaning that it is likely to buckle.

Two different levels of buckling have to be considered: global and local buckling.

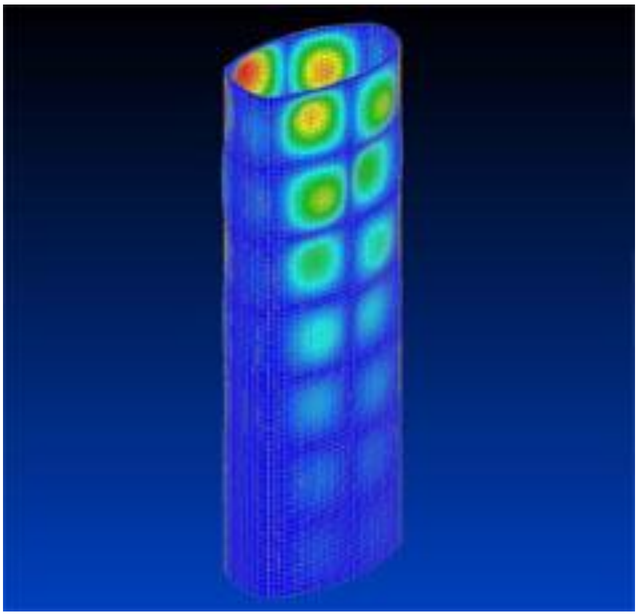


Figure 10 Buckling FEM analysis of a mast tube

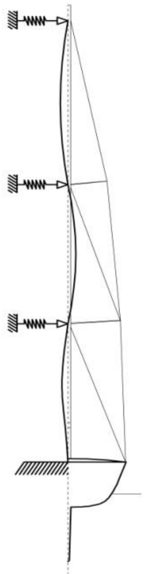


Figure 9 Global buckling of the mast between spreaders

Apart from the inertia of the section, the length of the panel (distance between two spreaders sets) is the critical parameter to consider for buckling resistance.
Several others parameters can influence the mast buckling resistance, like holes for halyards, attachments fittings for booms and pool.

3.1.3 Stays

The primary role of stays in a rig is to support the mast, working in conjunction with the spreaders. Stays are designed specifically as tension-only members, as they have the added advantage of improved material properties over compression members that have to deal with buckling and other non-linear failure modes.

It is also worth mentioning that stays in addition to only be able to support tension, become slack under compression. As mentioned in the first chapter, stays are made of wire or thin rod and have very low bending “stiffness”, such that they will sag under their own weight.

Slack stays or shrouds can lead to detachment of cap shrouds or damages due to fatigue and repeated shocks. To prevent the shrouds from becoming slack while sailing a pretension is applied to the rig.

The angle of the diagonal shrouds to the mast is a critical parameter. The wider is the angle, the lower will be the compression on the mast. For this reason angles below 10 ÷ 12 degrees are not recommended.

3.2 Spreaders

Spreaders act as small compression struts whose role is to improve the angle of the stays to the mast. They pull aside shrouds from the mast. They are mainly loaded with compression but are also subjected to bending and shear loads.

Most of the spreaders attachment allow o rotation on the y axis this avoid having any bending moment on the y axis

Rotations on the z axis are blocked. This permit to block the mast and to prevent pumping (movement of the mast in the fore/aft plane, occurring in case of strong pitch movements)

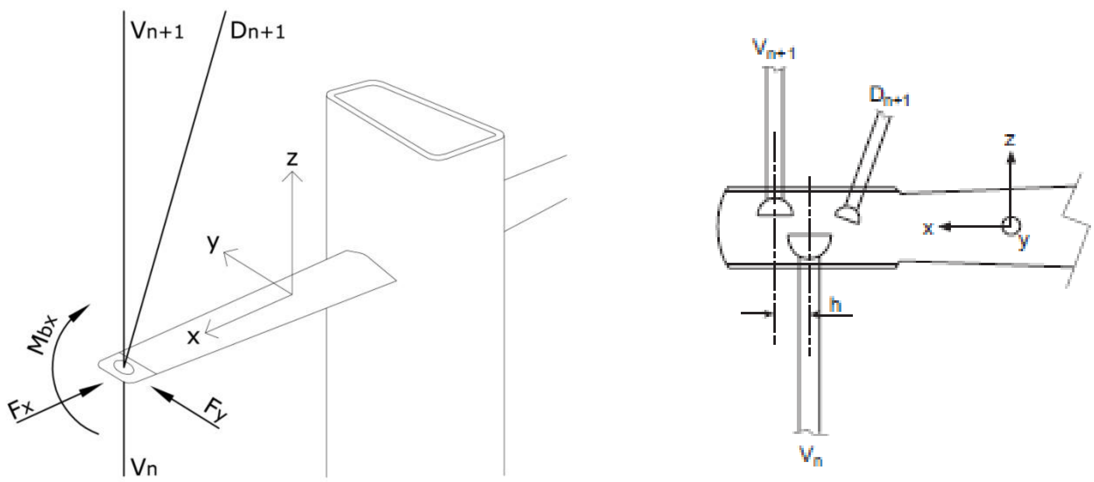


Figure 11 global view of spreader fitting (left) and spreader tip detail (right)

The dimensions of the spreaders greatly influence the mast mechanical behaviour and performances.

Design considerations

Today's tendency in rig design is to use wide spreaders, having a wide staying base. The reason is the leverage to support the heeling moment is increased. This permit to decrease the mast tube inertia and therefore induce some weight savings.

An second trend is the use of swept spreaders.

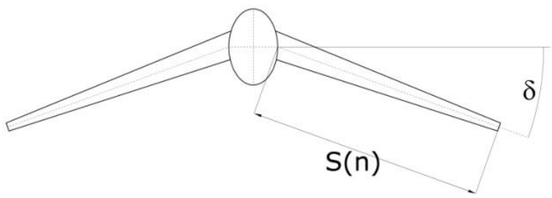


Figure 12 Top view of swept spreader arrangement

The main effect of the swept spreaders is to give the mast some fore/aft support from the side shrouds in addition to the usual transvers support. Since the loads from transverse support are large, these rigs tend to be locked up and unable to alter their mast bend easily. This means that runners and checkstays are no more of primary importance in the standing of the mast.

On the opposite a rig for a racing yacht does need to be altered to be able to suit different sail shape according to the different wind conditions the boat is facing. For these reasons swept spreaders and wide chain plate do not suit for racing yachts.

3.3 Dynamic behavior due to inertia.

One of the most challenging part in the design of a rigging concerns its behavior under dynamic loading either caused by wind gust or by the boat movements in rough sea.

3.4 Pre-tensioning

A Pre-tensioning of the rig is set to avoid slack leeward cap shrouds, when sailing at high heeling angles In a real sailing situation having slack shrouds is not acceptable for safety reasons. Cap shrouds can suffer damages if they are not maintained in tight position.

When the mast is stepped the pretensions is obtained using a mast-jack which is a ram used to push up the mast base vertically. Some metal shims are then inserted between the mast base and the keel and the ram is removed.

4. FAILURE MECHANISM

A mast has many failure mode possibilities. Nevertheless the combination of high dynamic loads and buckling failure is most encountered one. This type of situation is likely to happen in downwind condition when the boat starts broaching or is stopped by a wave at high speed. In upwind conditions waves can also induce pic loads leading to failures.

These aspects are currently under investigation but, up to now, it is difficult to have reliable results. The consequence of these, and other, uncertainties is that the range of safety coefficients becomes very wide and it is very difficult to choose the correct one. Too much severe loads will result in very safe but low performances rigging; too much optimistic loads will result in good performances but unreliable rigging.

This choice does not depend only on technical aspects but also on the skill of the crew: it is obvious that the safety level of a racing yacht cannot be the same of a cruise one.

CHAP 4 SAIL MECHANICS

1. DESCRIPTION SAILS

1.1 intro

The main property of soft sails is probably their adjustability to very different wind conditions. Their shape changes a lot. With a 3D model implementation it can be possible to take into account those variations.

1.2 generalities

1.2.1 sails typology

It is possible to establish a typology in the various types of sails. This typology is based on the way they are connected to the boat.

Those aspects are important to take into consideration given that they will set the boundary conditions used for the FEM analysis.

Mainsail and mizaine sail.

Those types of sail are directly connected to the mast by their luff. The clew point is usually connected to a boom. This results in a very constrained sail.

Stay sail

As their name may suggest this type of sail is supported by a stay. The luff is connected to a stay.

The stays are cables with almost no bending stiffness (A certain bending stiffness can be considered in certain cases when the stays are equipped with furling systems). The forces developed by a stay sail will induce some bending in the stay which will in return influence the sail shape. This aspect has to be taken into account when designing the sail shape.

Free flying sail

Those sails are only connected to the boat by their tree point (clew, tack and halyard point).

Having all the edges free results in an unstable sail which as to be closely watched, especially on the luff.

Typical free flying sail are spinnakers or gennakers.

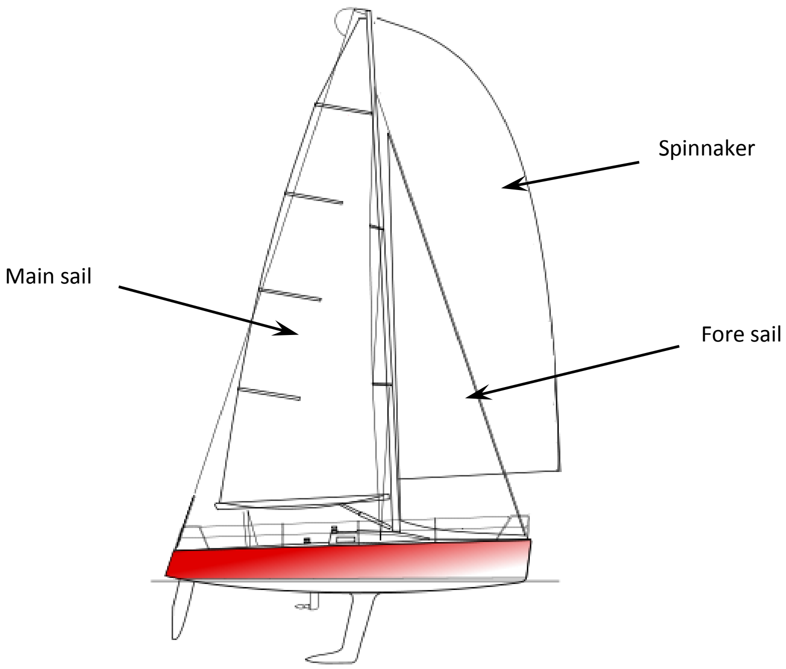


Figure 13 Typology of sails

1.3 materials

1.3.1 fabric cloth

Traditionally sails were made out fabric cloth. This type of material consists in a network of two different sets of fibers woven together perpendicularly.

Due to this manufacturing process fabrics cloth are anisotropic and offer poor resistance to shear. This last point is usually improved by coating sailcloth with resin filler.

1.3.2 Membrane cloth

The development of “load path” or “membrane” sail manufacturing technologies in the past 20 years has improved the aerodynamic efficiency of sails for all types of sailing boat. By aligning high strength fibers to the principal load paths, light weight films can be used in the unloaded areas removing redundant materials and resulting in substantially lighter sails with better shape retention. Almost all of the sail makers now offer some form of “membrane” sails, each with different manufacturing approaches and using a wide array of high strength materials for the load carrying elements (aramid, carbon, Vectran, Pentex etc.)

1.3.3 Cuben fiber and 3Di

Cuben fiber and North Sails 3Di are slightly different from the membrane sail in the sense that they are really composite material and not only fiber mesh enclosed between two membranes. As composite material they are made of fibers

One area of continued development is in advanced engineered composite fabrics such as Cuben™ fiber and the new North Sails 3Di system. In these systems the fibers are reduced to monofilaments in very light weight films that can then be arranged in the desired orientation before being consolidated. These fabrics thus do away with the weight penalties associated with films and scrims and some of the adhesive weight that is present in laminate sail production.

1.4 mechanics of sails

A shell structure is defined as a surface structure that supports tensile and compressive stress only and in which bending stiffness is negligible. When the thickness tends to zero, a shell is called a membrane. In this case, the material can only resist tension. Examples of similar structures are textile and thin laminate structures such as sails.

When subject to uniaxial compression a membrane wrinkles and slackens when subject to biaxial compression. These effects represent an important non-linearity that is not taken into account in a conventional linear stress-strain formulation.

CHAP 5 SIMULATION OF A SAIL DEFORMATION

1. POSSIBILITIES OVERVIEW AND CHOICE OF THE MODEL.

So far the loads applied in a fem mast analysis are defined using rules. Those rules are using strong simplifications.

The aim of this work was to investigate the possibilities of developing a simple and yet accurate model for predicting the efforts applied on the mast for scantling purpose.

With such a kind of model it is possible to investigate nonlinear behavior, preload on halyard and clew, dynamic effects of gusts.

This model has to be implemented in a FEA software, in the present case Ansys mechanical.

Several ways of modeling sail are possible. The first one, and most evident consist in modeling the sail with membrane elements.

Another possibility consists in considering the sail fabric as being equivalent to cables. The cable net model offers the possibility of orienting the mechanical characteristics of the element and thus reproducing the anisotropy of the sail cloth.

2. CABLE NET: ANALYSIS

2.1 Catenary model

Modeling the sail with a cable net requires focusing first on the elementary problem of the catenary. This problem is well known and as analytical solutions.

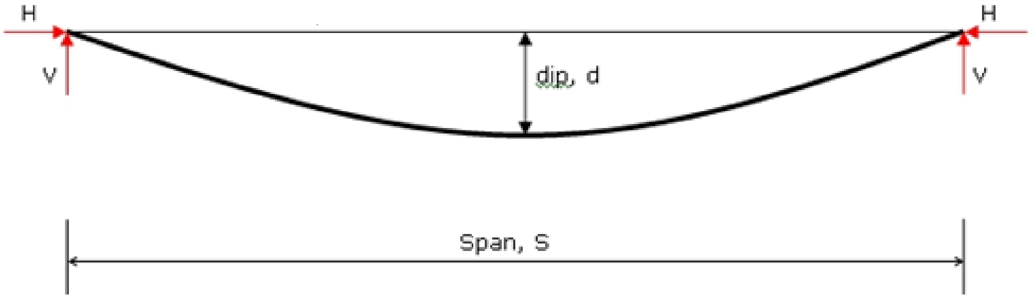


Figure 14 Scheme of the catenary problem

The horizontal and vertical reactions:

$$H = \frac{wS^2}{8d}$$

$$V = \frac{wS}{2}$$

The tension in the cable is given by the following expression.

$$T = \sqrt{H^2 + V^2}$$

By analyzing the expression of the horizontal force we can deduce that if the cable is absolutely straight (d = 0), the horizontal force will be infinite.

In order to get close to the reality, the depth of the catenary or cable net has to be taken into account.
If we consider it in the case of the sail, this will mean that as the camber is decreasing, the tension T will be increasing.

This justifies the need to work with a sail model having a 3D geometry and not with a flat sail model.

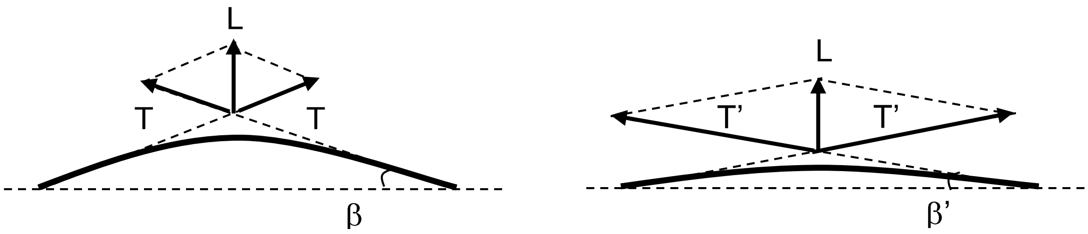


Figure 15 Different sail shapes resulting in force tension forces. (D. Boote)

2.2 cable net

The string network model is an extension of the model of the string, with the aim of calculating the deformation of a thin two-dimensional flexible structure.

The string network model is made of two families of string, the weft and the warp. Their elastic modulus can be different.

This will lead to strongly anisotropic mechanical properties which have to be taken into account. But this is also an advantage in the sense that it is then possible to reproduce the anisotropy of sail cloth.

In addition to modeling the weft and warp the shear strength can be modeled by adding some bias elements.

2.3 Different cable net model sail

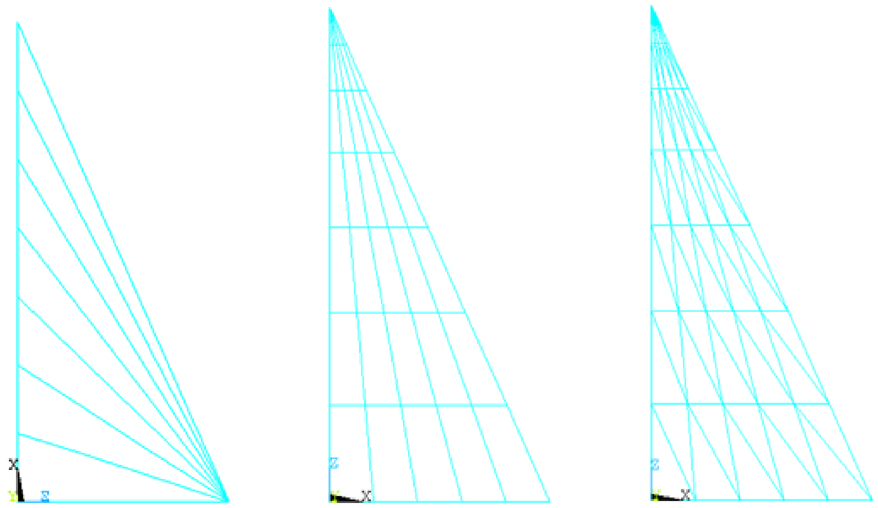


Figure 16 Cable net mesh possibilities.

Several meshing pattern can be used. The one based on square elementary surface is probably the most common to use, especially in the pre-processing part.

The vertical cables can be oriented radiating from the head or tack point.

3. CABLE NET SAIL FEA: CHOICE OF THE BEST SUITING ELEMENT

The choice of the element is a crucial part of the simulation and is strongly influencing the results especially in terms of stability of the model during the analysis and thus in terms of convergence of the computation.

A cable is an ideally flexible structure which is not capable of supporting compression. Under negative stress, a cable modifies its geometry to cope with these conditions. The deformation of the cable does not take into account its curvature.

These characteristics induce functional and numerical difficulties in the computation of a finite element cable net.

The two different possibilities offered by ANSYS for cable elements are the following:

link 10

The Link10 is a 3-D spar element featuring a uniaxial tension-only (or compression-only). With the tension-only option, the stiffness is removed if the element goes into compression (simulating a slack cable condition).

Link 8

The Link8 is also a 3-D spar element with uniaxial tension-compression feature. Each node as three degrees of freedom: translations in the nodal x, y, and z directions. As in a pin-jointed structure, no bending of the element is considered.

The choice between those two elements is uneasy.

According to the guidelines provided by ANSYS :
If the purpose of the analysis is to study the motion of the elements (with no slack elements), a similar element which cannot go slack, such as LINK8, should be used instead.
LINK10 should also not be used for static convergence applications where the final solution is known to be a taut structure but a slack condition is possible while iterating to a final converged solution. (Source: ANSYS Structural guide)

4. LOAD CASE AND BOUNDARY CONDITIONS.

4.1 Assumptions regarding the load case

The first assumption regarding the loads applied on the sail was to consider a uniform pressure on the entire surface of the sail.

Wing gradient and 3D aerodynamic induce effects were neglected. The variation of aerodynamic load along the chord was also not taken into account.

The pressure is uniform on all triangular elements.

The external force vector of a triangular element is deduced, by multiplying the pressure by the surface and by the unit vector perpendicular to the surface.

4.2 Load calculation for the test case model

The boat is considered in equilibrium at the SWA (Safe Working Angle, usually 30°), the righting moment then is equal to the healing moment.

The healing moment is created by the combination of the aerodynamic and hydrodynamic force. If the distance between the center of effort of the sail and the center of lateral resistance is known, then the force generated by the sail can be calculated.

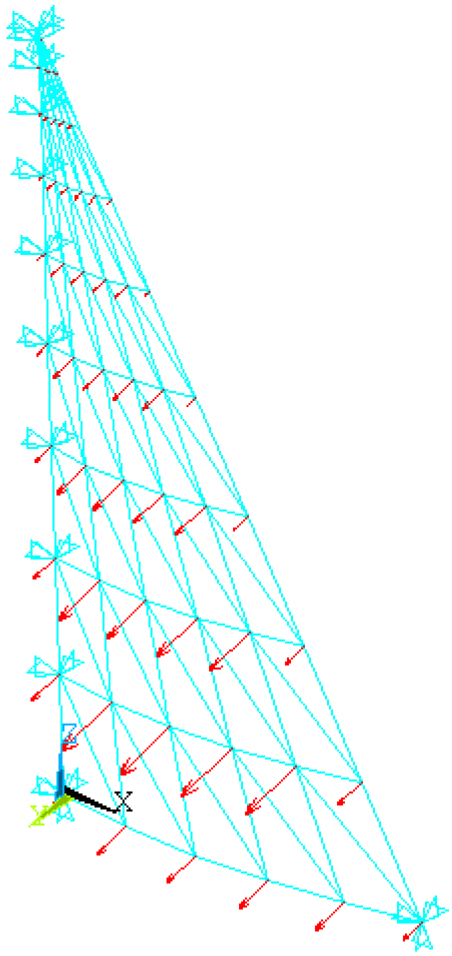


Figure 17 Load applied on the nodes of the sail

For the purpose of the study it was chosen to analyze a triangular mainsail that could fit a 10m cruiser sailboat.

The parameters of the test case are

Sail:

Foot: 4m

Luff: 9m

Distance between CLR and sail center of effort: 7m

Righting moment: 1.2T.m

The force developed by the sail is:

$$F = \frac{RM_{30°}}{CoE_{Sail}CLR}$$

$$F = 171\ N$$

4.3 Boundary conditions

On the 3 points (clew, tack, head) the sail is constrained for all translations and let free to rotate.

The nodes located on the luff of the sail are free to move rotate and to move vertically but are blocked laterally and longitudinally.

All the other points are free to rotate and translate.

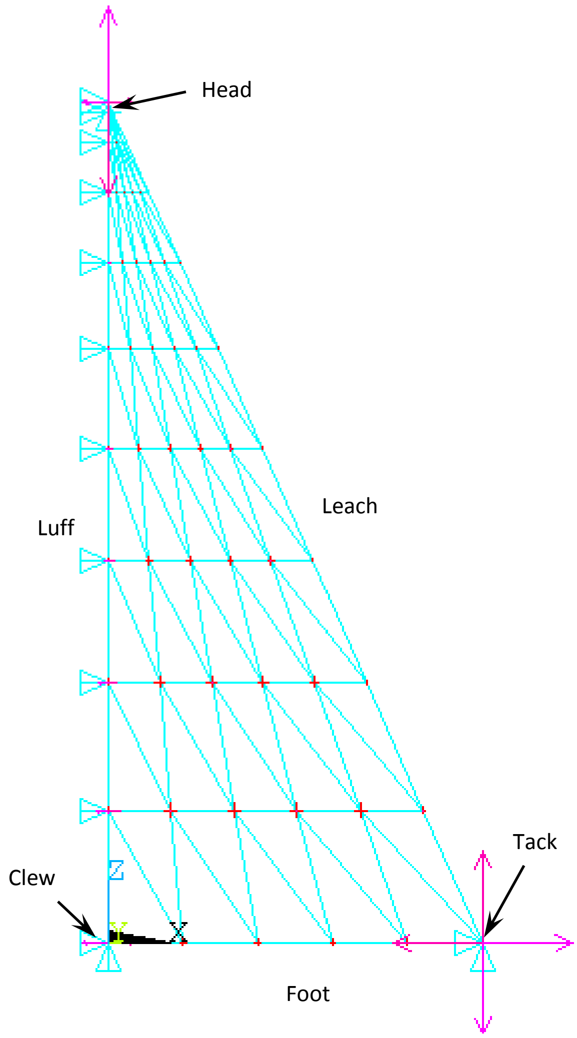


Figure 18 view of the boundary conditions

5. PRE-PROCESSING OF THE SAIL MODEL USING MATLAB.

5.1

A full set of parameters is required to generate the sail model. In order to be able to vary them easily a pre-processing routine was developed using Matlab.

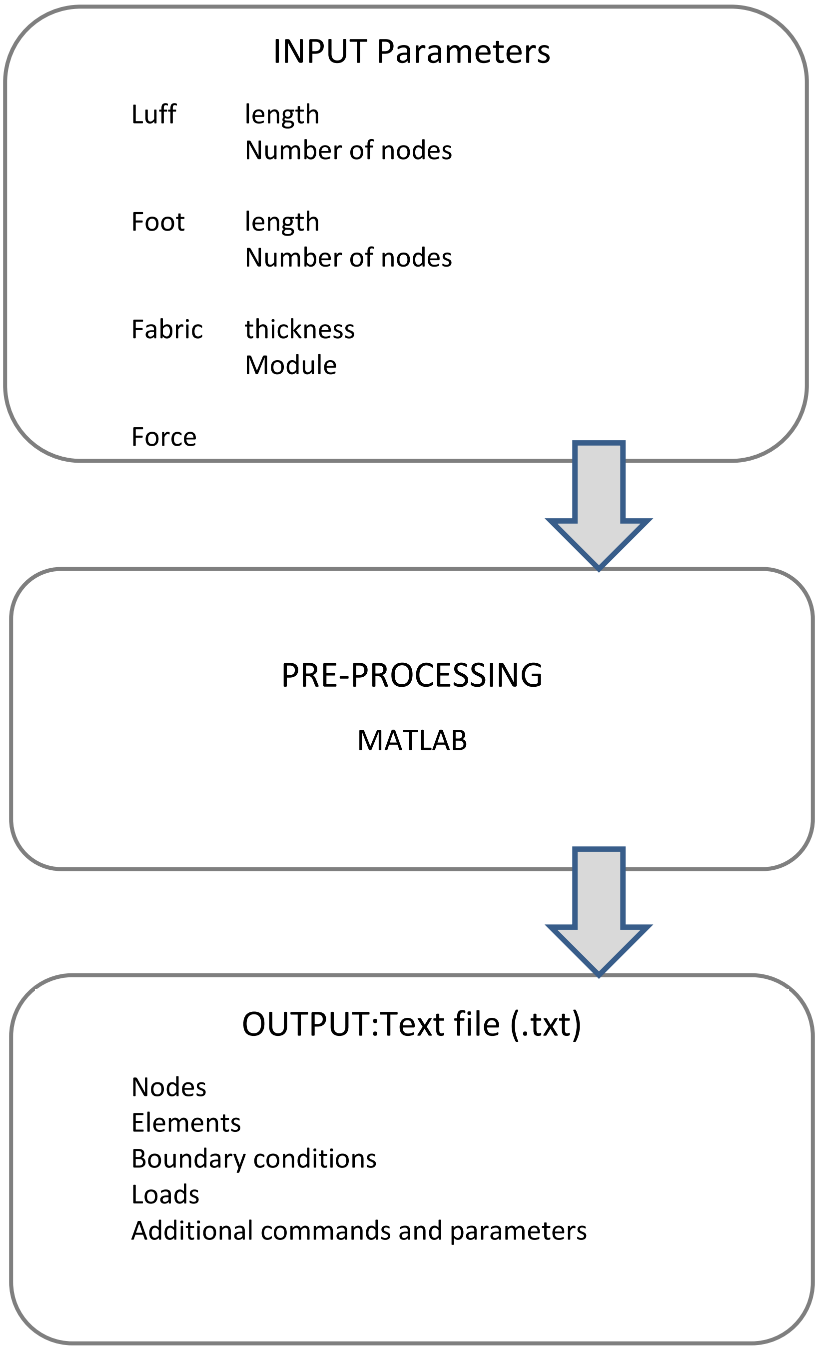


Figure 19 Sail model pre-processor

5.2 Pre-processor workflow

The Matlab pre-processor is performing a sequence of steps

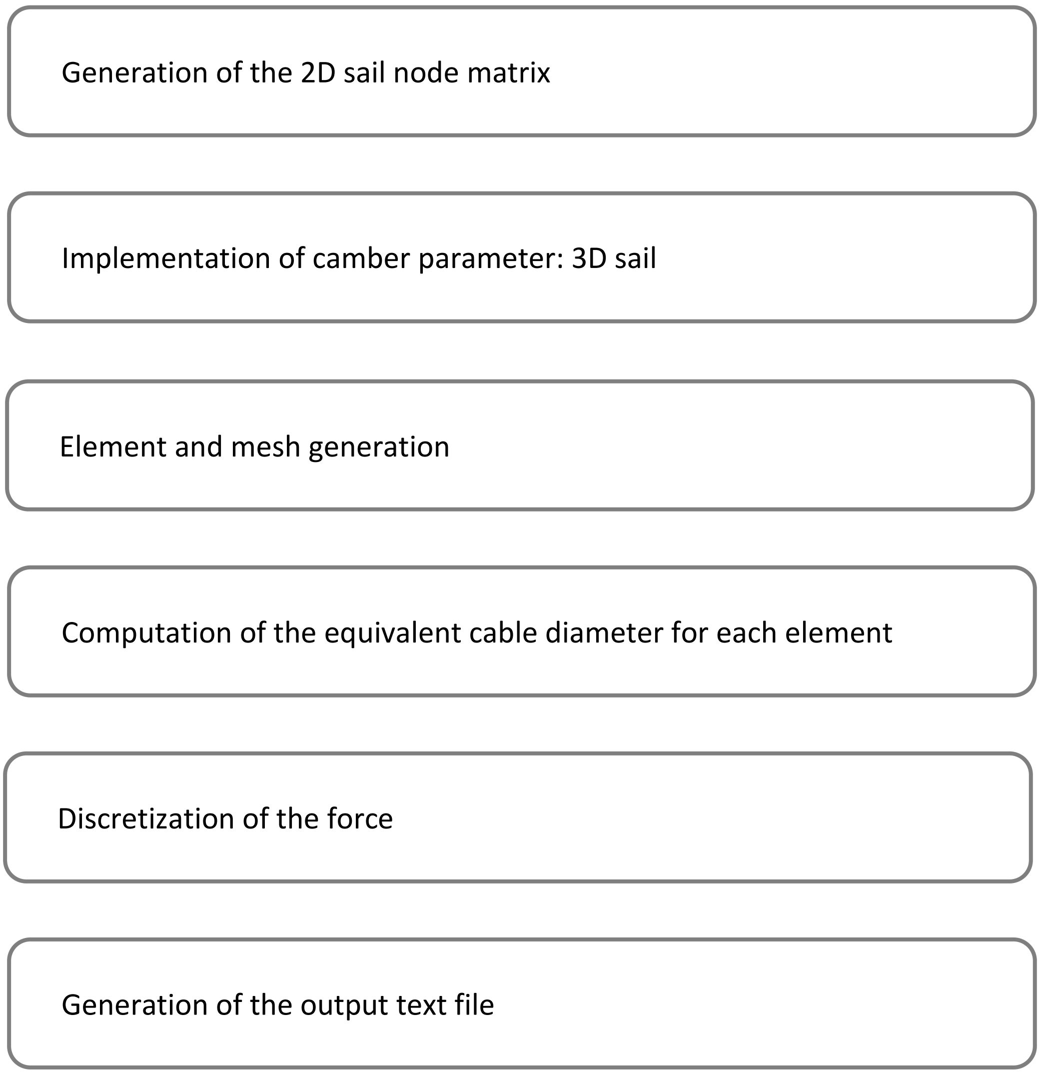


Figure 20 Workflow of the pre-processor

5.3 Principles of calculation used in the pre-processor.

5.3.1 Discretization of cables diameter.

Each cable element is representative of a surface. The equivalence between the 2D surface and the cable is obtained through the diameter of the corresponding cable.

This implies the need to compute the area of each elementary surface formed by the elements and the diameter of the corresponding cable.

Figure 21 illustrate the need to adjust the cable diameter. If no adjustment is performed the sail on the right would be much stiffer than the left one.

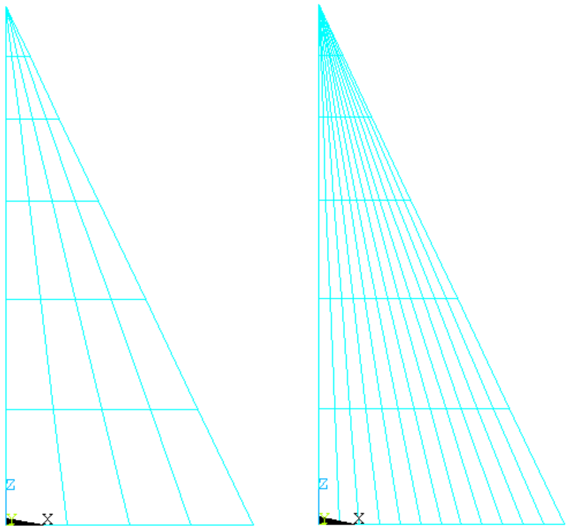


Figure 21 Sail models with different node density

5.3.2 Discretization of the aero force

The force also has to be discretized according to the number of nodes used in the model.

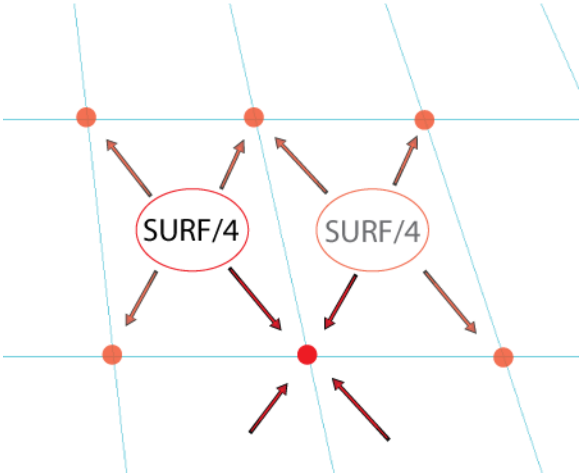


Figure 22 Principle used for force discretization

The principle of this discretization consists in calculating the "Surface Weight" of each node. This weigh represent the surface surrounding a node. The more the surface around a node is important the more will his weight be high.

This calculation is performed by dividing the area of each elementary surface composed by the elements and to distribute this value on the associated nodes.

5.3.3 Variable node density along luff

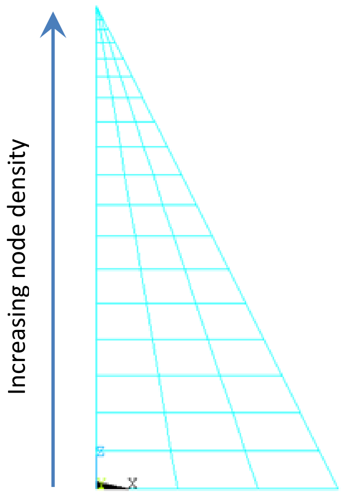


Figure 23 Variable node density along luff

In order to avoid too important changes in the square elementary surface aspect ratio, an additional parameter has been introduced to vary the node density. As it is possible to notice on Figure 23, the node density is increasing on the luff to become higher close to the head point of the sail.

5.4 Additional parameters

5.4.1 Pre-strain

A pre-strain can be applied to the cable element. This has the consequence of stabilizing the cable net and improving the convergence of the computation. Nevertheless the parameter value needs to be carefully chosen. Too much pre-strain would lead to a model too stiff and make convergence difficult to reach.

It is also important to remember that, apart from those stability and convergence considerations, the pre-strain will also influence the values of the reactions forces, possibly leading to unrealistic results.

5.4.2 Free edges stiffness

The rigidity of the free edges is another parameter influencing the stability of the model. Increasing the diameter of the element composing the free edges can lead to better stability and faster convergence. Nevertheless as for the pre-strain the difficulty is to find the right level for this parameter. Too much difference between the diameter of the edges and the diameter of the rest of the element leads to incorrect results.

5.4.3 Pre-tensioning by sail point displacement.

In a real situation a sail is submitted to a pre-tension applied by the halyard and by the sheet. This leads to increase the tension in the leech of the sail and to stabilize it.

This phenomenon can be reproduced in the finite element model by applying a displacement to the head or tack point.

6. SIMULATION RESULTS

6.1

After many trials and parameters combination testing, it was possible to obtain some sail deformations. Different sets of mesh density combination where tried.

Figure 24 shows the sail deformation. From a qualitative point of view, the deformation patterns are correct. The maximum deformation is located at the correct place.

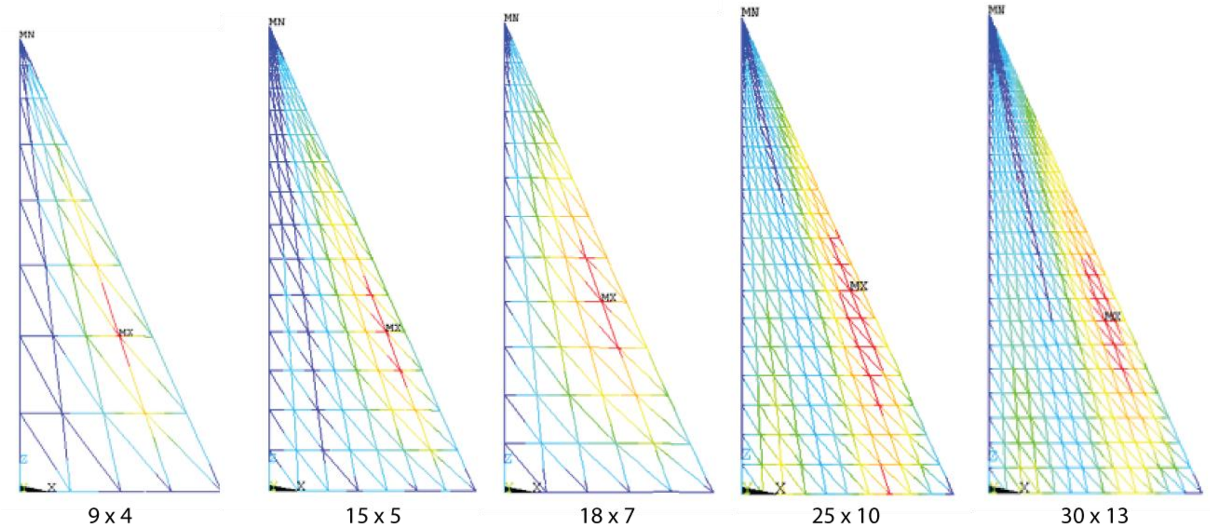


Figure 24 Results of sail deformations for different mesh density

6.2 Reaction forces.

In the following tables are displayed the reaction forces at the 3 points of the sail for different mesh density. No real convergence is achieved by increasing the mesh density. Some additional investigations needs to be performed in order to reach a more reliable model.

Clew	x	y	z
	[N]	[N]	[N]
9x4	-5,74E-02	-1,05E-02	-5,83E-02
18x7	1,88E-02	-3,80E-03	-3,10E-02
25x10	-0,015814	-0,0030767	-0,034793
30x13	-0,067593	-0,012465	-0,087042

tack	x	y	z
	[N]	[N]	[N]
9x4	0,86116	-0,041339	-1,4763
18x7	0,51865	-2,81E-02	-0,91615
25x10	0,54578	-2,85E-02	-0,91248
30x13	0,47366	-1,77E-02	-0,90869

head	x	y	z
	[N]	[N]	[N]
9x4	-0,60342	-7,55E-03	1,473
18x7	-0,35054	-0,012391	0,94717
25x10	-0,27519	-1,08E-02	0,94728
30x13	-0,28564	-1,16E-02	0,99581

7. CONCLUSION AND POSSIBLE DEVELOPMENTS.

The simulation of deformation of the cable net sail is still very unstable especially when reaching a high number of elements (more than 300)

Regarding the material characteristics chosen for the cable element some investigation toward nonlinear behavior should be done. Using tension only elements leads to a great instability and no convergence unless applying a high pre-strain. Unfortunately this high pre-strain is interfering with the results.

Regarding the finite element itself, additional investigations have to be performed regarding the stability and convergence of highly nonlinear deformation

The addition of rigid elements reproducing the battens of the sails would probably bring more stability to the model. Those elements would also help to get results closer to the reality as sails are fitted with those rigid elements.

New geometries is probably the most promising way of investigation, especially the radial clew configuration (diagonal element radiating from clew toward the luff)

CHAP 6 FINITE ELEMENTS ANALYSIS OF A SUPER YACHT MAST

1. GENERAL DESCRIPTION OF THE MAST

The design of the mast used for this study is similar to the design of the masts fitting the 56 m sloop series developed by Perini Navi.

The model developed for the analysis has the same geometry and proportions with however some slight variations in dimensions for confidentiality reasons.

Figure 25 56m sloop "Salute" sailing with full main sail and genoa.

Figure 26 Side view of the Perini navi 56m sloop

This fem analysis is not meant to be a “design phase” procedure, but is performed to check the results from previous analytical calculations and to find out the pre-tensioning load needed to be applied in order to have a mast working in safe conditions when sailing at healing angles close to the SWA (Safe Working Angle).

1.1 Technical specifications of the boat.

Length overall: 56 m

Beam (max): 11.52 m

Draught (keel down): 9.83 m

Displacement full load: 543.4 T

1.2 Technical specifications of the Rig.

Rig type: Sloop, keel stepped mast, aluminium

Length of the mast tube: 73m.

Lateral rigging

The mast is fitted 6 sets of spreaders with 22°Sweep angle

The shrouds are Nitronic 50 rod with a vertical plus diagonal configuration between each spreader.

The mast is fitted with 3 headstays supporting different foresails. Those stays are in rod Nitronic50.

The longitudinal stays are composed of a single backstay in Nitronic 50 rod and a paire of Kevlar runners.

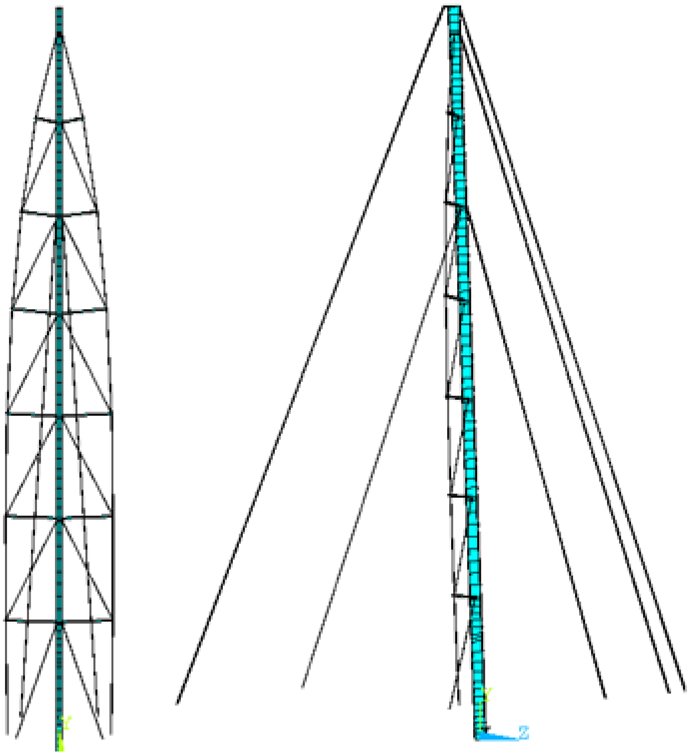


Figure 27 Front and side view of the mast model

2. Boundary conditions

2.1 Mast step

The mast step is constrained for in translations.

As mentioned before the mast is stepped on the keel and crosses the deck. On the deck the mast is constrained in the longitudinal and transversal direction. The mast tube has the possibility to move vertically.

2.2 Spreaders

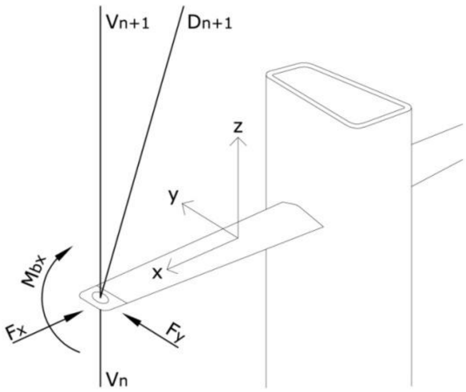


Figure 28 Spreader arrangement

On the mast the spreaders are blocked in all translations and can rotate around the Y axis (see Figure 28 Spreader arrangement)

The tips of the spreaders are attached to the shrouds but are free to rotate. No moments can be transmitted.

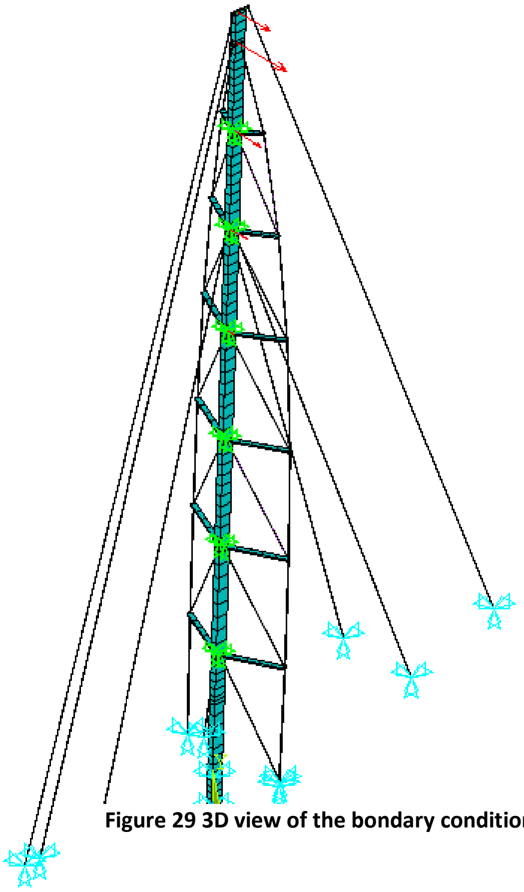


Figure 29 3D view of the bondary conditions

2.3 Stays

All stays are blocked in translation and are free to rotate on the chainplate attachment.

The same boundary conditions are applied on the attachment to spreaders and mast. (For diagonal and vertical shrouds)

3. LOADS

The loads are calculated in accordance to the rules edited the Germanischer Lloyd classification society; "Design and Construction of large modern yacht rigs".

For a complete mast study all ordinary sailing conditions have to be studied. It includes upwind beating, reaching and broad reaching under appropriate sail configurations for light, moderate, strong and stormy wind conditions, such as:

– Full main, working jib, genoa or reacher

– Several reef stages main, working jib, reefed jib, stay sail

– Spinnaker only.

– Others and special configurations for special rigs. (Such as mizzen stay sail).

In the case of this thesis only full main/genoa configuration will be analysed.

3.1 Transverse sail loads.

In order to calculate the forces generated by the sails a set of geometrical data are required.

CLR	Height of the center of lateral resistance of the underwater body (including appendages)	[m]
A_m	Mainsail area, (projected laterally)	[m²]
A_f	Foresail area, (projected laterally)	[m²]
P	Vertical position of mainsail head	[m]
E	Mainsail foot length	[m]
I	height of fore triangle	[m]
J	fore sail foot length	[m]

3.1.1 Main sail loads

For this load case the mainsail is considered fully hoisted (no reef).

The righting moment is considered in that case at 25° of heel.

Righting moment	[N.m]	RM	5120000

Centre of lateral resistance of the underwater body	[m]	CLR	0,8

Main			
Gooseneck z	[m]		13,260
Mainsail hoist	[m]	P	75,280
main sail area	[m²]	Am	769
Mainsail foot	[m]	E	
Centre of effort for Mainsail	[m]	CoEm	34,840
Transverse force from mainsail	[N]	Ftm	80271

Items	z_i	C_{im}	$C_{im} \times z_i$	F_{im}	
gooseneck	14,064	0	0	0	[N]
spreader 1	18,01	0	0	0	[N]
spreader 2	28,021	0	0	0	[N]
spreader 3	37,821	0	0	0	[N]
spreader 4	47,621	0,05	2,38105	2846,14316	[N]
spreader 5	57,021	0,15	8,55315	8538,42949	[N]
spreader 6	66,019	0,25	16,50475	14230,7158	[N]
main headboard	76,081	0,3	22,8243	17076,859	[N]

$$\sum_{i=1}^{n}(C_{im} \times z_i) = 50,26325$$

$$F_{tmd} = 56922,8633 \text{ [N]}$$

With :

$$F_{tmd} = \frac{F_{tm} \times CoEmCLR}{\sum_{i=1}^{n}(C_{im} \times z_i)}$$

3.1.2 Foresail loads

In this case the foresail considered is the genoa. (medium sail, between staysail and reacher)

Righting moment	[N.m]	RM	5120000

Centre of lateral resistance of the underwater body	[m]	CLR	0,8

Fore sail			
foresail area	[m²]	Af	726
heigh of of fore triangle	[m]	I	
base of fore triangle	[m]	J	
Centre of effort for Mainsail	[m]	CoEf	29,007
Transverse force from foresail	[N]	Ftf	75783,2688

Items	z_i	C_{if}	$C_{if} \times z_i$	F_{if}	
tack	8,405	0,3	2,5215	19659,3454	[N]
clew	11,549	0,3	3,4647	19659,3454	[N]
head	71,21	0,4	28,484	26212,4605	[N]
	$\sum_{i=1}^{n}(C_{im} \times z_i) =$		34,4702		
		$F_{tfd} =$	65531,1514	[N]	

With :

$$F_{tfd} = \frac{F_{tf} \times \ CoEfCLR}{\sum_{i=1}^{n}(C_{if} \times z_i)}$$

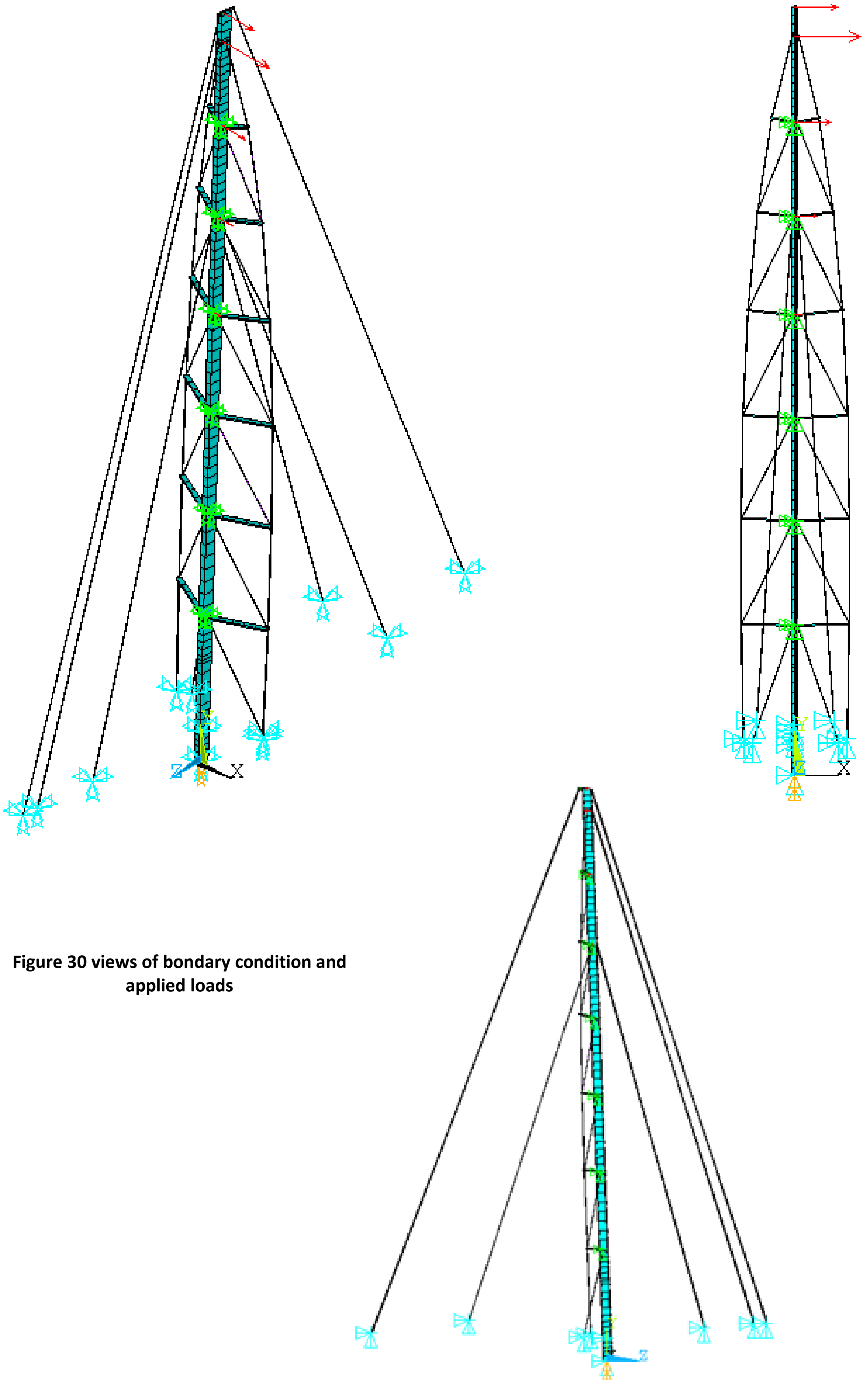


Figure 30 views of bondary condition and applied loads

3.2 Pre-tensioning of the rig

A Pre-tensioning of the rig is set to avoid slack leeward cap shrouds, when sailing at heeling angles smaller than the "SWA". (A margin as to be taken into account in case of over heeling). In a real sailing situation having slack shrouds is not acceptable for safety reasons. Cap shrouds can suffer damages if they are not maintained in tight position.

The pre-tensioning of the rigging is calculated by the designer.

When the mast is stepped the pretensions is obtained using a mast-jack which is a ram used to push up the mast base vertically. Some metal shims are then inserted between the mast base and the keel and the ram is removed.

In a mast fem simulation two ways of reproducing this pretension can be used in accordance with the aim of the analysis.

If the pretension load is already known (after analytical calculation) then this load can be directly applied to the mast tacking care not to constrain the displacement in the direction of the applied load in order to permit the displacement of the mast base.

A displacement can be applied to the mast base and with an iterative process the correct pre-tensioning can be determined. This way of proceeding is well adapted to a design phase but can be time consuming if no automated optimization loop is programmed.

This mast base displacement procedure will be used for the current analysis.

3.3 Mast analysis results: Pre-tensioning setting

The analysis consists in determining the right pre-tensioning and once it is done verifying that the scantlings of all the rigging elements are correct.

Initial phase

The initial phase of the finite element analysis is starting with the following conditions:

The mast is fully loaded with the sail loads and no displacement is applied on the mast base.

initial phase

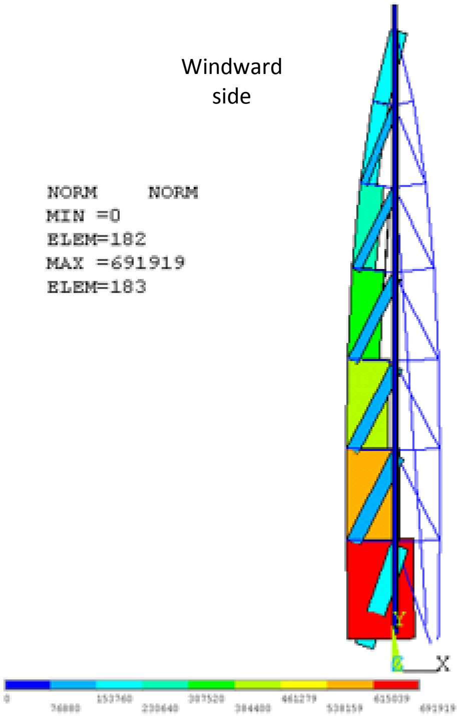


Figure 31 Normal Forces in shrouds with NO pretension

It is possible to notice on Figure 31 that all the shrouds (verticals and diagonals) on the leeward side are slack (Normal forces are equal to zero).

With no pre-tensioning, the lateral displacement of the mast head is 1010mm.

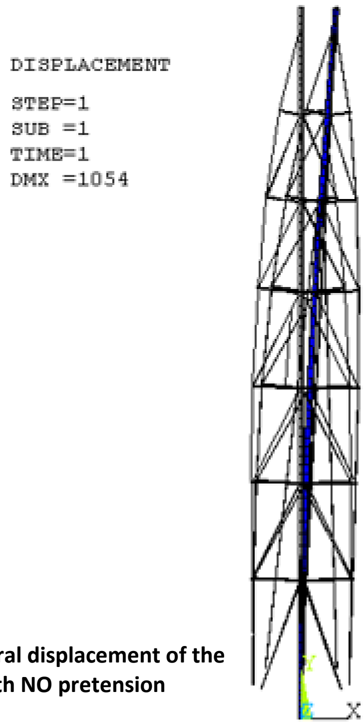


Figure 32 Lateral displacement of the mast with NO pretension

Final phase: pretension applied

At this point the pre-tension is applied. As mentioned before the pre-tensioning is obtained by pushing vertically on the mast base. The correct displacement is determined by an iterative process: the displacement is increased step by step until reaching sufficient tension in the leeward shrouds.

As the heel angle increases the rig element that will first become slack is the D7, leeward.

To avoid excessive cap shrouds movements and prevent any failure, a tension load of 5T is considered to be adequate.

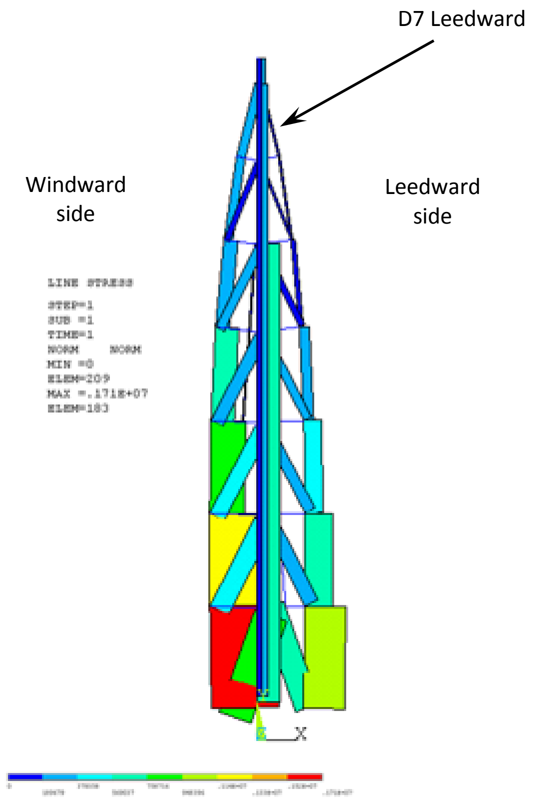


Figure 33 Normal forces in shrouds with pretension

Load in D7 leeward: 4.8 T

Mast base load. 394 T

Windward V1 stress : 387 MPa inducing a load of 124T in the corresponding chainplate.

Mast head displacement:

Mast base vertical displac

This displacement is the applied during the tuni

pretension is inducing a pressure of 180T in the mast base.

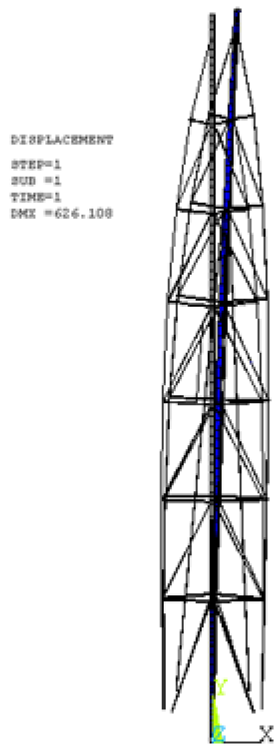


Figure 34 Lateral displacement of the mast with pretension.

3.4 Mast analysis results: checking the stress in the mast tube.

3.4.1 Shrouds

As mentioned before all stays are made out of Nitronic 50 rod (excepted runners).

The elastic limit considered is 350 MPa.

As seen in the previous part, the maximum stress occurs in the V1. The stress value is 170 MPa which is under the elastic limit of Nitronic 50.

3.4.2 Mast tube

The mast tube is made out of aluminium series 6000. To keep a security margin the elastic limit considered will be 150 Mpa.

Aluminium alloy	$\sigma_{0.2\%}$ [N/mm^2]	σ_U [N/mm^2]	ε_U	HB	E [N/mm^2]
AA 6063	150	195	12%	80	69000
AA 6061	235	255	8%	80	69000
AA 6082	255	305	10%	90	69000

The stress considered is Von-Mises stress.

All parts of the mast are subjected to stress lower than 150 MPa except a zone located at the deck level. On this point the mast is blocked laterally and longitudinally by the deck.

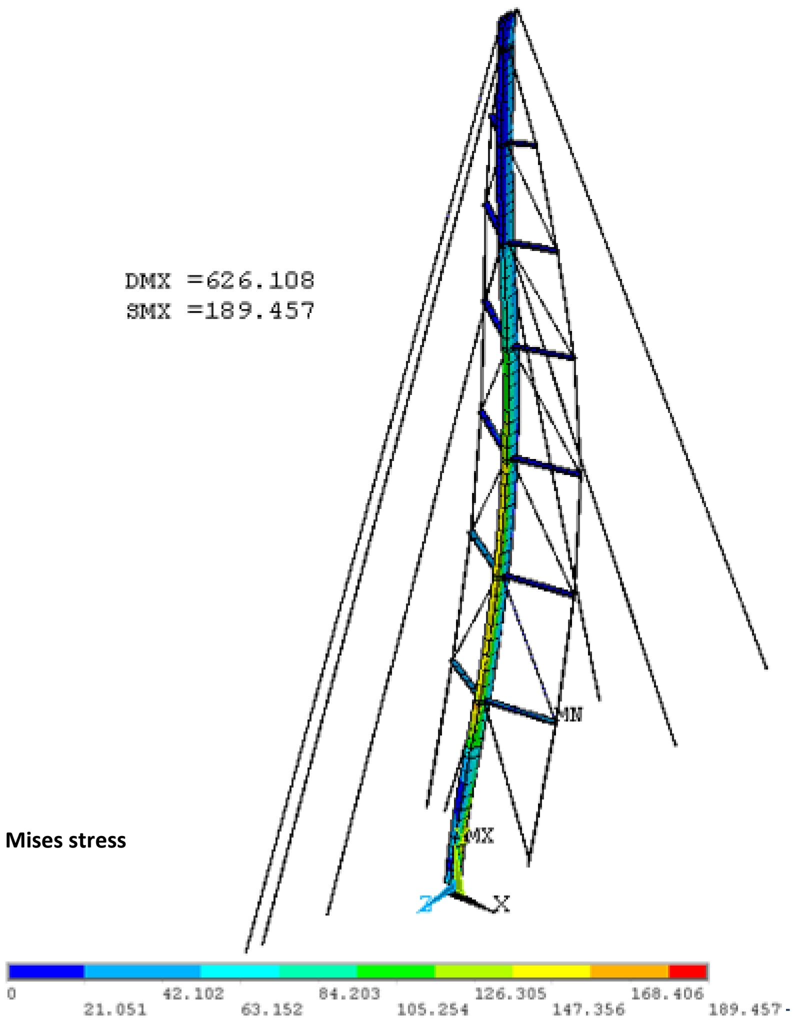


Figure 35 Von Mises stress

In the finite element model a single node constrain is simulating this blockage. This is leading to a stress concentration higher than it would be in the reality.

In reality the mast is stepped, tuned and then blocked by casting a resin. This leads a to higher contact surface which is also softer avoid this high stress concentration.

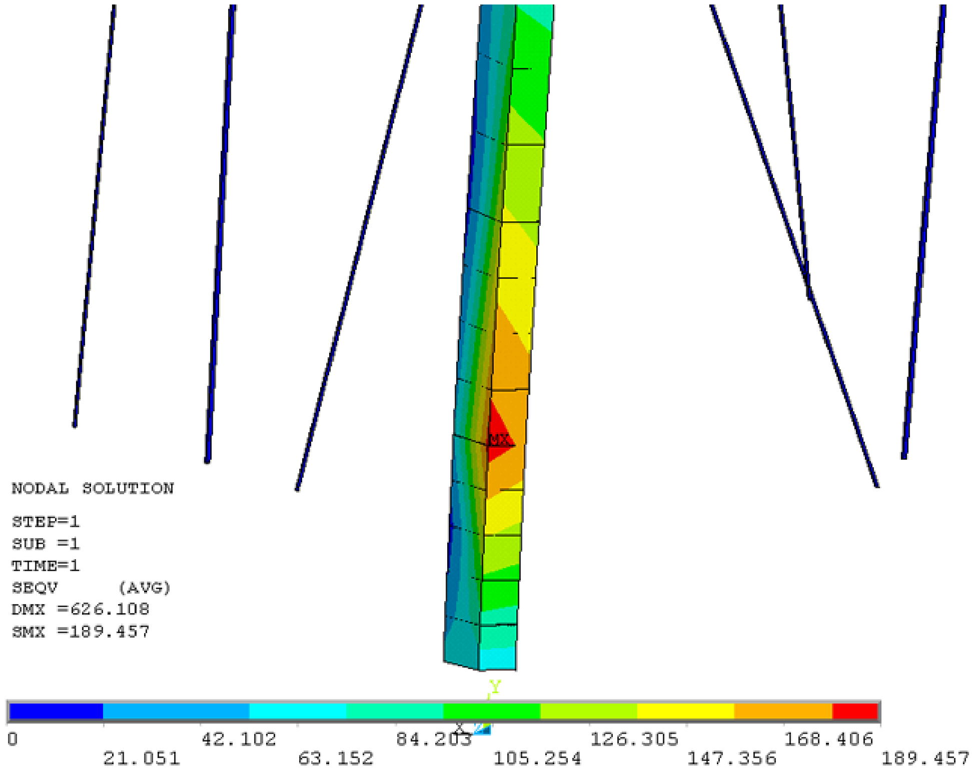


Figure 36 Deck support stress concentration

CHAP 7 ONBOARD DATA ANALYSIS

Comparing the predicted values to real measured values is the ultimate and best way to validate a prediction model. Some research teams have been working in that direction, creating "lab boats" fully equipped with sensors and then comparing the onboard measurements with results obtained by Finite Element Analysis. While being extensive in terms of recorded parameters those test campaign remained limited to well defined sailing conditions. The reality of the sailing conditions faced by a super yacht is much wider and sometimes out of the sailing "good practices"

Perini Navi in collaboration with the University of Genova has been developing an onboard data measurement recording system. It has been specifically designed for the Perini Navi yachts in ketch configuration. Onboard installation has been suited for the S/Y Riela and her onboard navigation system.

The aim of the system is to continuously monitor several different parameters relevant to the mast and rigging behavior by managing several different sensors installed on shrouds, main mast and inside the ship, and, additionally, by collecting data from the onboard data logger system and storing them together with ones acquired by the system itself

Many hours of data measurement have been recorded with the previous system and one of the aims this thesis was to process the data in order to be able to analyze them.

For a given sailing condition the level for a same signal varies around a mean value, and it is therefore necessary to perform statistical analysis. The data recording system fitting the Yacht Riela is based on monitoring systems. The first one is the "boat" monitoring system recording parameters such as speed, heel angle,… The second system is specifically dedicated to monitor the mast efforts. Those two systems are recording data with a different sampling frequency leading to impossibility, with the given tools, to perform data correlation and statistical analyses.

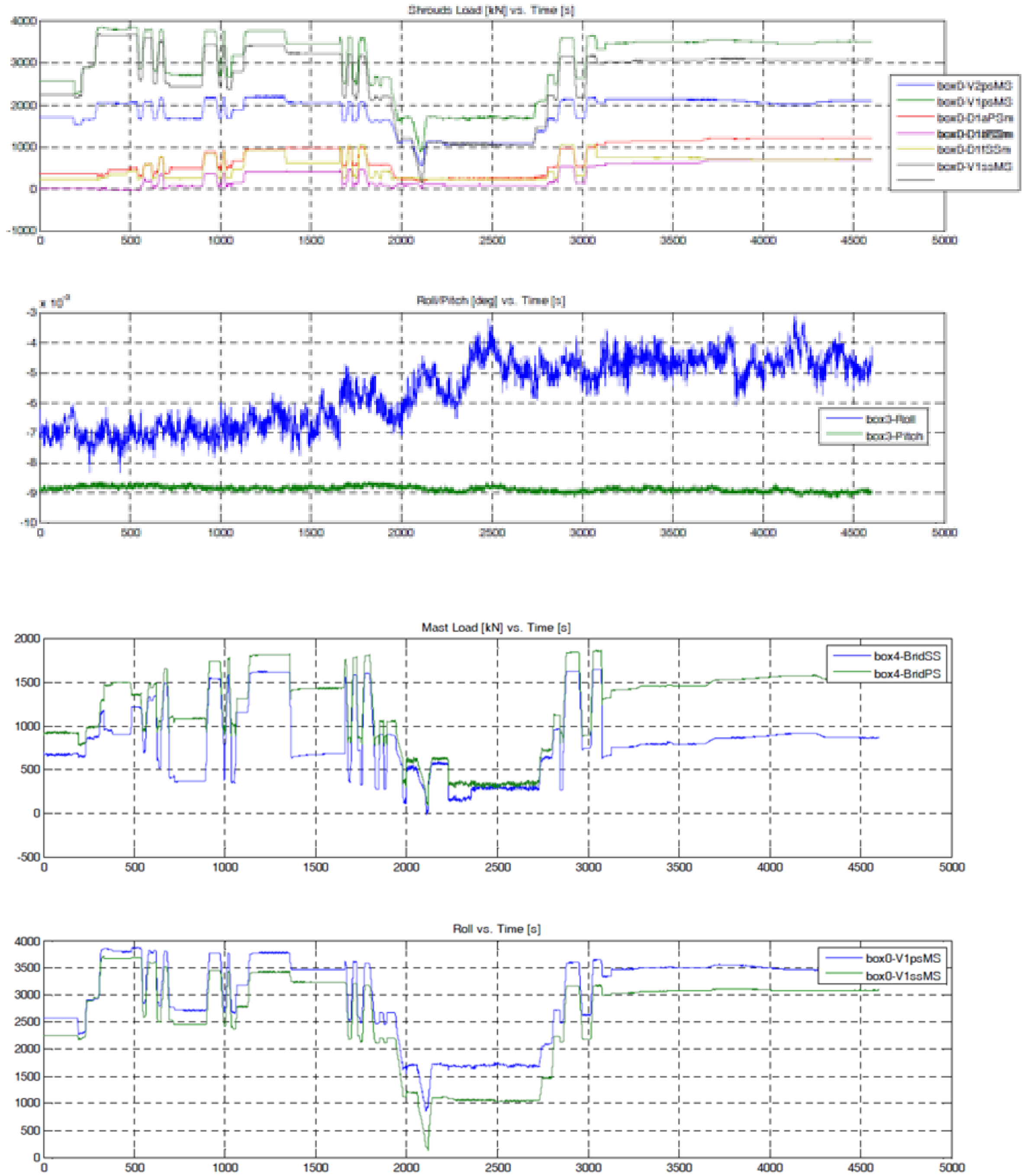


Figure 37 Plots of recorded sailing data (Courtesies Perini Navi and University of Genoa)

CONCLUSION

The simulation of sail deformation is starting to work well and to give results. Some additional investigations have to be performed to obtain a fully reliable sail deformation model.

Once this model is operational the next step consist in including it a Finite Element mast model and to perform a simulation.

Results given FEM sail method can then be compared to the classical Rule method. In addition to direct comparison a validation with real onboard measurement would permit to fully validate the method.

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APPENDIX A:MATLAB CODE FOR SAIL PRE-PROCESSING

```
%-------------------------------------------------------------------------
% Sail Pre-processing
%-------------------------------------------------------------------------

clear all;
close all;
clc;
fclose('all');
clearvars -global;

%-------------------------------------------------------------------------
%Data input
%-------------------------------------------------------------------------
% Variable Description:
%           *luff_length - length of the sail luff
%           *foot_length - length of the sail foot
%           *Nluff - Number of Elements along luff
%           *Nfoot - Number of Elements along foot
%           *coordinates - The nodal coordinates of the mesh
%               -----> coordinates = [node X Y Z]
%           *nodes - The nodal connectivity of the elements
%               -----> nodes = [element node1 node2......]


luff_length = 9 ;  %luff length
foot_length = 4 ;  %foot length
Nluff = 8;      %Number of elements luff
Nfoot = 5;      %Number of elements in foot

Heeling_Force = 200;

fabric_thick = 0.4e-3;
fabric_modulus = 2e9;

Elem_type = 'LINK8';

prestrain = 1e-6;

prestrain_Luff = 0.0000001;
prestrain_Leech = 0.00001;
prestrain_Foot = 0.00001;

Diam_Luff = 0.001;
Diam_Leech = 0.001;
Diam_Foot = 0.001;


Uz_halyard = 0;

Ux_clew = 0;
```

```
Uz_clew = 0;




%--------------------------------------------------------------------------
% Computation of Geometrie
%--------------------------------------------------------------------------
nel = Nluff*Nfoot;          % Total Number of Elements in the Mesh

% Luff and foot discretization
npluff = Nluff+1 ;
npfoot = Nfoot+1;


nluff = cos(linspace(pi/2,0,npluff))*luff_length;
nfoot = linspace(0,foot_length,npfoot);


[L F] = meshgrid(nluff,nfoot) ;


% Convert grid to cartesian coordinates
ZZ = L;
XX = (F/luff_length).*(luff_length-L);

YY = zeros(npfoot,npluff);




%-----Adding camber coordinates--------------------------------------------

LL=[XX(npfoot,:)];

m = npluff;
for i = 1:npluff
        C(:,i) = XX(:,i)./LL(:,i);
end

YY = (0.0952*C.*C.*C-0.3401*C.*C+0.2449*C);


n = npluff;
for i = 1:n
        YY(:,i) = YY(:,i).*LL(:,i);
end


coordinates = [XX(:) YY(:) ZZ(:)] ;
coordinates(isnan(coordinates)) = 0;      %removing NaN
```

```
%------------------------------------------------------------------------
% Node matrix
%------------------------------------------------------------------------

nnode = npluff*npfoot;

NodeNo = [1:nnode];
NodeMat = reshape(NodeNo,npfoot,npluff);
NodeMat =NodeMat';

A=NodeMat(end,1);
NodeMat(end,:)=A;


%-----Horizontal elements---------------------------------------------------
count=1;

for i=2:Nluff
    for j=1:Nfoot
        B = ones(1,3);
        B(1,1:2)=NodeMat(i,j:j+1);
        HorizElem(count,:)=B;


        %---Comptutation of element length
        X = (coordinates(B(1),1) - coordinates(B(2),1))^2;
        Y = (coordinates(B(1),2) - coordinates(B(2),2))^2;
        Z = (coordinates(B(1),3) - coordinates(B(2),3))^2;

        dist = (X + Y + Z)^(0.5);
        HorizElem(count,3) = dist;
        %--------------------------------
        count=count+1;
    end
end

%Foot elements
count=1;
    for j=1:Nfoot
        B(1,1:2)=NodeMat(1,j:j+1);
        FootElem(count,:)=B;


        %---Comptutation of foot element length
        X = (coordinates(B(1),1) - coordinates(B(2),1))^2;
        Y = (coordinates(B(1),2) - coordinates(B(2),2))^2;
        Z = (coordinates(B(1),3) - coordinates(B(2),3))^2;

        dist = (X + Y + Z)^(0.5);
        FootElem(count,3) = dist;
        %-------------------------------------
        count=count+1;
    end



%-----Vertical elements-----------------------------------------------------
count=1;
```

```
for i=2:npfoot-1
    for j=1:Nluff
        B(1,1:2)=NodeMat(j:j+1,i);
        VertElem(count,:)=B;


         %---Comptutation of foot element length
        X = (coordinates(B(1),1) - coordinates(B(2),1))^2;
        Y = (coordinates(B(1),2) - coordinates(B(2),2))^2;
        Z = (coordinates(B(1),3) - coordinates(B(2),3))^2;

        dist = (X + Y + Z)^(0.5);
        VertElem(count,3) = dist;
        %-------------------------------------
        count=count+1;
    end
end

%Luff elements
count=1;
    for j=1:Nluff
        B(1,1:2)=NodeMat(j:j+1,1);
        LuffElem(count,:)=B;


        %---Comptutation of foot element length
        X = (coordinates(B(1),1) - coordinates(B(2),1))^2;
        Y = (coordinates(B(1),2) - coordinates(B(2),2))^2;
        Z = (coordinates(B(1),3) - coordinates(B(2),3))^2;

        dist = (X + Y + Z)^(0.5);
        LuffElem(count,3) = dist;
        %-------------------------------------

        count=count+1;
    end


%Leech elements
count=1;
    for j=1:Nluff
        B(1,1:2)=NodeMat(j:j+1,npfoot);
        LeechElem(count,:)=B;


        %---Comptutation of foot element length
        X = (coordinates(B(1),1) - coordinates(B(2),1))^2;
        Y = (coordinates(B(1),2) - coordinates(B(2),2))^2;
        Z = (coordinates(B(1),3) - coordinates(B(2),3))^2;

        dist = (X + Y + Z)^(0.5);
        LeechElem(count,3) = dist;
        %-------------------------------------

        count=count+1;
    end
```

```
%-----biais elements-------------------------------------------------------
count=1;

for i=1:Nluff-1
    for j=2:npfoot
        B=NodeMat(i,j);
        CC=NodeMat(i+1,j-1);
        BiaisElem(count,1)=B;
        BiaisElem(count,2)=CC;
        count=count+1;
    end
end


%--------------------------------------------------------------------------
% Force Discretisation
%--------------------------------------------------------------------------

nodes2(:,1) = reshape(NodeMat(2:npluff,1:npfoot-1),[],1);
nodes2(:,2) = reshape(NodeMat(2,2),[],1);
nodes2(:,3) = reshape(NodeMat(1:npluff-1,2:npfoot),[],1);


count=1;

for i=1:Nluff
    for j=1:Nfoot
        Pt1=NodeMat(i,j);
        Pt2=NodeMat(i+1,j);
        Pt3=NodeMat(i,j+1);
        TriElem(count,1) = Pt1;
        TriElem(count,2) = Pt2;
        TriElem(count,3) = Pt3;

        Pt1=NodeMat(i,j+1);
        Pt2=NodeMat(i+1,j);
        Pt3=NodeMat(i+1,j+1);
        TriElem(count+1,1) = Pt1;
        TriElem(count+1,2) = Pt2;
        TriElem(count+1,3) = Pt3;

        count=count+2;
    end
end



%-----Computation of Triangle area
[m,n] = size (TriElem);

for i=1:m
    for j=1:n
       a(i,j) = {coordinates(TriElem(i,j),:)};
    end
end
```

```
one = ones(1,3);

for i=1:m
    pt1=cell2mat(a(i,1))';
    pt2=cell2mat(a(i,2))';
    pt3=cell2mat(a(i,3))';

    mat = [pt1, pt2, pt3];
    x = mat(1,:);
    y = mat(2,:);
    z = mat(3,:);

    mat1 = [x; y; one];

    mat2 = [y; z; one];

    mat3 = [z; x; one];

    area= 0.5*((det(mat1)^2 + det(mat2)^2 + det(mat3)^2)^(1/2));
    TriElem(i,4)= area/3;

end
clear mat1 mat2 mat3;


%-----Force Discretisation-------------------------------------------------

sail_area = luff_length*foot_length*0.5;
P = Heeling_Force /sail_area;

true_node_num = npfoot*npluff -npfoot+1;
Nodal_Force = zeros(true_node_num,2);
Nodal_Force(:,1)=[1:true_node_num];

[m,n] = size (TriElem);

for i=1:m
    for j=1:3
        num_node = TriElem (i,j);
        surf = TriElem (i,4);
        Nodal_Force (num_node,2) = (Nodal_Force (num_node,2))+ surf;
    end
end

Nodal_Force (:,2) = Nodal_Force (:,2)*P;



%--------------------------------------------------------------------------
% Diameter Computation for VERTICAL elements
%--------------------------------------------------------------------------

%-----Node weight----------------------------------------------------------
Diam_VertElem = zeros(true_node_num,2);
Diam_VertElem(:,1)=[1:true_node_num];

[m,n] = size (FootElem);
for i=1:m
```

```
    for j=1:2
        num_node = FootElem (i,j);
        Length = FootElem (i,3);
        Diam_VertElem    (num_node,2)    =    (Diam_VertElem    (num_node,2))+
Length*0.5;
    end
end


[m,n] = size (HorizElem);
for i=1:m
    for j=1:2
        num_node = HorizElem (i,j);
        Length = HorizElem (i,3);
        Diam_VertElem    (num_node,2)    =    (Diam_VertElem    (num_node,2))+
Length*0.5;
    end
end

%-----Element diameter---------------------------------------------------

%-----Luff elements
[m,n] = size (LuffElem);
for i=1:m
        num_node = LuffElem (i,1:2);
        LuffElem(i,4)        =        (Diam_VertElem(num_node(1),2)        +
Diam_VertElem(num_node(2),2))/2;
        LuffElem(i,4) = (LuffElem(i,4) * fabric_thick * 4 *1/3.14)*(0.5);
%          LuffElem(i,4) = Diam_Luff;
end


%-----Leech elements
[m,n] = size (LeechElem);
for i=1:m
        num_node = LeechElem (i,1:2);
        LeechElem(i,4)        =        (Diam_VertElem(num_node(1),2)        +
Diam_VertElem(num_node(2),2))/2;
        LeechElem(i,4) = (LeechElem(i,4) * fabric_thick * 4 *1/3.14)*(0.5);
%          LeechElem(i,4) = Diam_Leech;
end

%-----Vertical elements
[m,n] = size (VertElem);
for i=1:m
        num_node = VertElem (i,1:2);
        VertElem(i,4)        =        (Diam_VertElem(num_node(1),2)        +
Diam_VertElem(num_node(2),2))/2;
        VertElem(i,4) = VertElem(i,4) * fabric_thick;
end




%-----------------------------------------------------------------------
% Diameter Computation for HORIZONTAL elements
%-----------------------------------------------------------------------


%-----Node weight--------------------------------------------------------
```

```
Diam_HorizElem = zeros(true_node_num,2);
Diam_HorizElem(:,1)=[1:true_node_num];

[m,n] = size (VertElem);
for i=1:m
    for j=1:2
        num_node = VertElem (i,j);
        Length = VertElem (i,3);
        Diam_HorizElem   (num_node,2)   =   (Diam_HorizElem   (num_node,2))+
Length*0.5;
    end
end

[m,n] = size (LuffElem);
for i=1:m
    for j=1:2
        num_node = LuffElem (i,j);
        Length = LuffElem (i,3);
        Diam_HorizElem   (num_node,2)   =   (Diam_HorizElem   (num_node,2))+
Length*0.5;
    end
end


[m,n] = size (LeechElem);
for i=1:m
    for j=1:2
        num_node = LeechElem (i,j);
        Length = LeechElem (i,3);
        Diam_HorizElem   (num_node,2)   =   (Diam_HorizElem   (num_node,2))+
Length*0.5;
    end
end

Diam_HorizElem(true_node_num,2)=0;

%-----Element diameter-----------------------------------------------------

%-----Foot elements
[m,n] = size (FootElem);
for i=1:m
        num_node = FootElem (i,1:2);
        FootElem(i,4)       =       (Diam_HorizElem(num_node(1),2)       +
Diam_HorizElem(num_node(2),2))/2;
        FootElem(i,4) = (FootElem(i,4) * fabric_thick * 4 *1/3.14)*(0.5);
%         FootElem(i,4) = Diam_Foot;
end


%-----Horizontal elements
[m,n] = size (HorizElem);
for i=1:m
        num_node = HorizElem (i,1:2);
        HorizElem(i,4)       =       (Diam_HorizElem(num_node(1),2)       +
Diam_HorizElem(num_node(2),2))/2;
        HorizElem(i,4) = HorizElem(i,4) * fabric_thick;
end
```

```
%-----------------------------------------------------------------------------
% OUTPUT
%-----------------------------------------------------------------------------

%-----Coordinates ---------------------------------------------------------
Num = [(1:nnode)' , coordinates];


fid = fopen('geom.txt', 'wt');
fprintf(fid, '%s\n','FINISH');
fprintf(fid, '%s\n','/CLEAR,START');
fprintf(fid, '%s\n','/PREP7');
fprintf(fid,  '%s\n','/TITLE,  cable  net,  square  elements,  stiff  free
bords');
fprintf(fid, '%s\n','ANTYPE,STATIC,NEW');

fprintf(fid, '%s%s\n','ET,1,',Elem_type);
% fprintf(fid, '%s\n','KEYOPT, 1, 2, 2');
% fprintf(fid, '%s\n','KEYOPT, 1, 3, 0');

fprintf(fid, '%s%E\n','MP,EX,1,',fabric_modulus);


fprintf(fid, '%s\n','!Nodes coordinates');

format = ['N,%u,%f,%f,%.3f\n'];


for row=1:nnode-Nfoot
    fprintf(fid, format, Num(row,1:4));

end

%-----Elements ------------------------------------------------------------

format1 = ['R,%u,%E,%E\n'];
format2 = ['REAL,%u\n'];
format3 = ['E,%u,%u\n'];

Elem_count = 1;

fprintf(fid, '\n%s\n','!Vertical elements');
[m,] = size(VertElem);
for row=1:m
    fprintf(fid, format1, Elem_count, VertElem(row,4),prestrain);
    fprintf(fid, format2, Elem_count);
    fprintf(fid, format3, VertElem(row,1:2));
    Elem_count = Elem_count+1;
end

fprintf(fid, '\n%s\n','!Horizontal elements');
[m,] = size(HorizElem);
for row=1:m
    fprintf(fid, format1, Elem_count, HorizElem(row,4),prestrain);
    fprintf(fid, format2, Elem_count);
    fprintf(fid, format3, HorizElem(row,1:2));
```

```
    Elem_count = Elem_count+1;
end

fprintf(fid, '\n%s\n','!Leech elements');
[m,] = size(LeechElem);
for row=1:m
    fprintf(fid, format1, Elem_count, LeechElem(row,4),prestrain_Leech);
    fprintf(fid, format2, Elem_count);
    fprintf(fid, format3, LeechElem(row,1:2));
    Elem_count = Elem_count+1;
end



fprintf(fid, '\n%s\n','!Luff elements');
[m,] = size(LuffElem);
for row=1:m
    fprintf(fid, format1, Elem_count, LuffElem(row,4),prestrain_Luff);
    fprintf(fid, format2, Elem_count);
    fprintf(fid, format3, LuffElem(row,1:2));
    Elem_count = Elem_count+1;
end

fprintf(fid, '\n%s\n','!Foot elements');
[m,] = size(FootElem);
for row=1:m
    fprintf(fid, format1, Elem_count, FootElem(row,4),prestrain_Foot);
    fprintf(fid, format2, Elem_count);
    fprintf(fid, format3, FootElem(row,1:2));
    Elem_count = Elem_count+1;
end



fprintf(fid, '\n%s\n','!Biais elements');
format1 = ['R,%u,%E,%E\n'];


[m,] = size(BiaisElem);
for row=1:m
    fprintf(fid, format1, Elem_count, 1e-6,prestrain);
    fprintf(fid, format2, Elem_count);
    fprintf(fid, format3, BiaisElem(row,1:2));
    Elem_count = Elem_count+1;
end


%-----Bondary conditions---------------------------------------------------

fprintf(fid, '\n%s\n','!Bondaries conditions');
format = ['D,%u,UX,,,,,UY\n'];
[m,n] = size(NodeMat);
for row=1:m-1
    fprintf(fid, format, NodeMat(row,1));
end
%-----
fprintf(fid, 'D,%u,UX,,,,,UY,UZ\n', NodeMat(1,1));

%-----
```

```
fprintf(fid, 'D,%u,UX,,,,,UY\n', NodeMat(1,end));
% fprintf(fid, 'D,%u,UX,%f\n', NodeMat(1,end),Ux_clew);
fprintf(fid, 'D,%u,UZ,%f\n', NodeMat(1,end),Uz_clew);

%-----Horizontal elements
fprintf(fid, 'D,%u,UX,,,,,UY\n', NodeMat(end,1));
fprintf(fid, 'D,%u,UZ,%f\n', NodeMat(end,1),Uz_halyard);




%-----Forces-----------------------------------------------------------

fprintf(fid, '\n%s\n','!Forces');
format = ['F,%u,FY,%.3f\n'];
[m,n] = size(Nodal_Force);
for row=1:m
    fprintf(fid, format, Nodal_Force(row,:));
end

fprintf(fid,'%s\n','NLGEOM,ON');
fprintf(fid,'%s\n','SSTIF,ON');


fprintf(fid,'%s\n','FINISH');

fprintf(fid,'%s\n','/SOLU');

fprintf(fid,'%s\n','SOLCONTROL,ON,ON');
fprintf(fid,'%s\n','NSUBST,20');
fprintf(fid,'%s\n','KBC,0');

fprintf(fid,'%s\n','STABILIZE,CONSTANT,ENERGY,0.1,MINTIME');

fprintf(fid,'%s\n','SOLVE');
fprintf(fid,'%s\n','FINISH');



fprintf(fid,'%s\n','/POST1');
fprintf(fid,'%s\n','PLDISP,2');
fprintf(fid,'%s\n','FINISH');

fclose(fid);





%--------------------------------------------------------------------
% Plotting the Finite Element Mesh
%--------------------------------------------------------------------

Initialization of the required matrices
nnel=2;
X = zeros(nnel,nel) ;
Y = zeros(nnel,nel) ;
```

```
Z= zeros(nnel,nel) ;



Elem_tot = [VertElem; HorizElem];
[m,] = size(Elem_tot);

% Extract X,Y coordinates for the (iel)-th element

  for iel = 1:m
      X(:,iel) = coordinates(Elem_tot(iel,:),1) ;
      Y(:,iel) = coordinates(Elem_tot(iel,:),2) ;
      Z(:,iel) = coordinates(Elem_tot(iel,:),3) ;
  end

% Figure
fh = figure ;
set(fh,'name','Preprocessing for FEA','numbertitle','off','color','w') ;
patch(X,Y,Z,'w')
title('Sail cable net') ;
% axis([0. L*1.01 0. B*1.01])
axis off ;
axis equal ;

disp 'Computation over';
```

APPENDIX B: MATLAB CODE FOR DATA PROCESSING

```
clear all;
close all;
clc;
fclose('all');
clearvars -global;

format compact
format short g;

%-----------------------------------------------------------------------
%             Directory Selection
%-----------------------------------------------------------------------
% dirname = uigetdir('C:\');

dirname    =    'C:\Documents    and    Settings\Pat\Mes    documents\Perini
Navi\Data\Nouveau dossier';

folder_content = dir(dirname);

%-----------------------------------------------------------------------
%             Listing and sorting files in selected directory
%-----------------------------------------------------------------------
File_list = {folder_content.name}.';


%-----Load files-----------------
localdep = cellfun(@isempty,regexp(File_list,'^.+(dls.txt)$', 'match'))';
Filelist_load=File_list(localdep);

Filelist_load =regexp(Filelist_load,'^.+(.txt)$', 'match');
Filelist_load=[Filelist_load{:}].';

Listpath_load         =          cellfun(@(x)         fullfile(dirname,x),
Filelist_load,'UniformOutput',false);


%-----DLS files------------------
Filelist_dls =regexp(File_list,'^.+(dls.txt)$', 'match');
Filelist_dls =[Filelist_dls{:}].';

Listpath_dls         =          cellfun(@(x)          fullfile(dirname,x),
Filelist_dls,'UniformOutput',false);




%-----------------------------------------------------------------------
%          LOAD FILES
%-----------------------------------------------------------------------
```

```
%---------------Creation of new file, headerlines insertion

newfile_load=fullfile(dirname,'LoadData.txt');
nb_col_load = 41;


a=Listpath_load(1);
a = char(a);


% -------------------------

fid = fopen(a);
    head_format = [repmat('%s\t', 1, 41') '\n\r'];
    headline_load = textscan(fid, head_format, 41, 'delimiter', '\t');
fclose(fid);

headline_load=[headline_load{:}];

headline_load(:,[6:9 14:17 25 31:33 37:38 41]) = [];

[nrows,ncols]= size(headline_load);

fid = fopen(newfile_load, 'wt');

ncols = ncols-1;

head_format = [repmat('%s\t', 1, ncols') '%s\n'];

for row=1:nrows
    fprintf(fid, head_format, headline_load{row,:});
end

fclose(fid);


% ---------------File convertion (comma ---> dot) and compilation

% convertion factors
%   [FileName,PathName,FilterIndex]    =   uigetfile('*txt',   'Selection   of
conversion file');
% Conv_totpath = fullfile(PathName,FileName);

Conv_totpath     =     'C:\Documents     and     Settings\Pat\Bureau\Nouveau
dossier\conversion.txt';

conv_format = [repmat('%f ', 1, nb_col_load')];

fid = fopen(Conv_totpath);
    factors   =  textscan(fid,  conv_format,  'HeaderLines',  3,'delimiter',
'\t', 'EmptyValue', 0);
fclose(fid);
factors = cell2mat(factors);

col_load = [repmat('%.6f ', 1, nb_col_load') '%*[^\n]'];
NumTxt_load = numel(Filelist_load);
```

```
for i = 1:NumTxt_load;

    b=Listpath_load(i);
    b = char(b);


    %-----Convertion : comma ---> dot ----
    file = memmapfile(b, 'writable', true );
        comma = uint8(',');
        point = uint8('.');
    file.Data( transpose( file.Data==comma) ) = point;
    delete(file)


    %-----Copy--------------
    fid = fopen(b);

        C = textscan(fid, col_load,'HeaderLines', 1, 'delimiter', '\t');

    fclose(fid);
    C = cell2mat(C);


    %-----Conversion Volt ---> unit-------
    [m,n] = size(C);
    for j = 1:m

     C(j,:) = C(j,:).*factors(1,:);

    end

    %-----Deleting columns and Paste---------------------------

    C(:,[6:9 14:17 25 31:33 37:38 41]) = [];

    dlmwrite(newfile_load, C, 'precision', '%.3f', '-append', 'delimiter',
'\t', 'newline', 'pc');

end
clear ('factors');




%---------------------------------------------------------------------------
%          DLS FILES
%---------------------------------------------------------------------------

%---------------Creation of new file, headerlines insertion

newfile_dls=fullfile(dirname,'DLSData.txt');
a=Listpath_dls(1);
a = char(a);

%---------------Headerlines copy
```

```
nb_col_dsl = 56;

fid = fopen(a);
%       head_format  =  ['%s  '  repmat('%*[^\t]',  1,  3')  repmat('%*[^\t]  %s',
1,%      26')  '\n\r'];

    head_format = [repmat('%s ', 1, 56') '\n\r'];
    headline_dls = textscan(fid, head_format, 'delimiter', '\t');



fclose(fid);

headline_dls=[headline_dls{:}];
headline_dls(:,[1:36 39:56]) = [];

%---------------Headerlines paste

[nrows,ncols]= size(headline_dls);
% head_format = [repmat('%s\t', 1, 56') '%s\n'];

fid = fopen(newfile_dls, 'wt');

for row=1:nrows
     fprintf(fid, '%s\t%s\n', headline_dls{row,:});
end

fclose(fid);


%---------------File convertion (comma ---> dot) and compilation

NumTxt_dls = numel(Filelist_dls);

col_dls  =  [repmat('%*[^\t]',  1,  36)  '%.6f  %.6f'  repmat('%*[^\t]',  1,  18)
'%*[^\n]'];


for i = 1:NumTxt_dls;

    b=Listpath_dls(i);
    b = char(b);

    %-----Convertion : comma ---> dot
    file = memmapfile(b, 'writable', true );
        comma = uint8(',');
        point = uint8('.');
    file.Data( transpose( file.Data==comma) ) = point;
    delete(file);

    %-----Copy/paste--------------
    fid = fopen(b);

        C = textscan(fid, col_dls, 'HeaderLines', 1, 'delimiter', '\t');

    fclose(fid);
```

```
   %-----Deleting columns and Paste---------------------------

%     C(:,[1:36 39:56]) = [];

    C=[C{:}];

    [nrows,ncols]= size(C);

    for row=1:nrows
        if  (C(row,:) ~= 0.0), dlmwrite(newfile_dls, C(row,:), 'precision',
'%.3f', '-append', 'delimiter', '\t', 'newline', 'pc');
        else
        end;
    end
end


% ----------
% fwrite(C, '%s\t%s\n', headline_dls{row,:});
% ----------

clear ('C');

disp ('Data processing over');




%-------------------------------------------------------------------------
%           Plotting Load files
%-------------------------------------------------------------------------
col_load = [repmat('%.6f ', 1, 26') '%*[^\n]'];
col_dls = [repmat('%.6f ', 1, 2') '%*[^\n]'];

fid = fopen(newfile_load);
load_matrix = textscan(fid, col_load, 'HeaderLines', 1, 'delimiter', '\t');
fclose(fid);
load_matrix=[load_matrix{:}];

fid = fopen(newfile_load);
dls_matrix = textscan(fid, col_dls, 'HeaderLines', 1, 'delimiter', '\t');
fclose(fid);
dls_matrix=[dls_matrix{:}];


% unit_format = [repmat('%s ', 1, nb_col_load') ' %*[^\n]'];
% fid = fopen(Conv_totpath);
% units_chanel = textscan(fid, unit_format, 'delimiter', '\t');
% fclose(fid);
% units_chanel=[units_chanel{:}];



%---Chanel 1-HEEL angle (dls file)------

% chanel_label_1 = units_chanel(1,numcol_1);
```

```
y_dls = dls_matrix(:,2);
x_dls = dls_matrix(:,1);
x_dls = x_dls(:) - x_dls(1);


%---Chanel 2-------
numcol = 35;
% chanel_label_2 = units_chanel(1,numcol);
yload_1 = load_matrix(:,25);
xload_1 = load_matrix(:,1);
xload_1 = xload_1(:) - xload_1(1);


% clear ('load_matrix');
% clear ('dls_matrix');


figure;
plot(x_dls, y_dls, 'r');
axis tight;
% legend(chanel_label_1, chanel_label_2);
ylabel('Load [kN]');
hold on

plot(xload_1, yload_1, 'b');
axis tight;
xlabel('TIME [sec]');
ylabel('Load [kN]');
```