The Carbon and PBO Rig for the „sailOvation“
- Finite Element Analysis -

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1. Introduction

The “sailOvation” is a German innovation bearer for the cruising yacht of the future. She is a 30 ft long canting keel yacht and bound to plane on a close reach. The project is sponsored by the German yachting magazine “segeln-magazin” and involved companies to build her.
The rig is a key term to enable the “sailOvation” to plane on a close reach. The aim is to design and to construct a rig that is strong and stiff enough to resist the big righting moment from the canting keel and that is also as light as possible. A global geometrical nonlinear finite element analysis is performed for the rig. Two load cases are investigated: dock tune and sailing close hauled. The rig is constructed out of carbon for the spars and out of PBO fibres for the transverse standing rigging.
Results of first trial runs show that the “sailOvation” is able to start semi-planing on a close reach and that there is still a potential to raise speeds by optimizing rig and sail trim.

2. The sailing yacht “sailOvation” and her rig

The sailing yacht „sailOvation“ is designed by M. O. v.Ahlen and constructed by the boatyard Janssen and Renkhoff. The design is in the tension field of the contradicting demands of cruising and planing on a close reach. The main numbers are:

L = 9.00 m	D = 2.00 m
LWL = 8.92 m	Depl. = 1.7 t light weight, 1.9 t loaded
B = 3.43 m	Keel weight = 0.7 t
BWL = 2.00	RM25 = 2,775 kgm

Everything possible was done to reduce drag and weight. The hull is built in carbon-SPRINT sandwich. The big carbon and PBO rig has a lot of power (**figure 1**). A special feature is the so called X-keel arrangement (**figure 2**). The “sailOvation” has two keels that can be canted individually. The forward keel carries the bulb. It is canted to windward up to 50° to enhance the righting moment. The aft keel is canted to leeward as much as the yacht heels. It will be adjusted vertical to produce optimal side force. Two asymmetric dagger boards were no alternative, for they would reduce the space under deck for cruising accommodations. Two hydraulic rams move the keels. The “sailOvation” has no engine. The energy to move the keels comes from a bank of 12 V batteries. 180 tacks are possible with fully charged batteries.

Semi-planing on a close reach is only possible with the ability to carry a large sail area for propulsion force combined with a small total weight. Racing dinghies like a Flying Dutchman can semi-plane on a close reach. They have a length/displacement ratio of about 7.5 and higher. The length/displacement ratio and the sail carrying number of the “sailOvation” are:

$$\frac{L_{WL}}{V^{(1/3)}} = 7.2 \qquad \frac{S_A^{(1/2)}}{V^{(1/3)}} = 5.2 \cdot$$

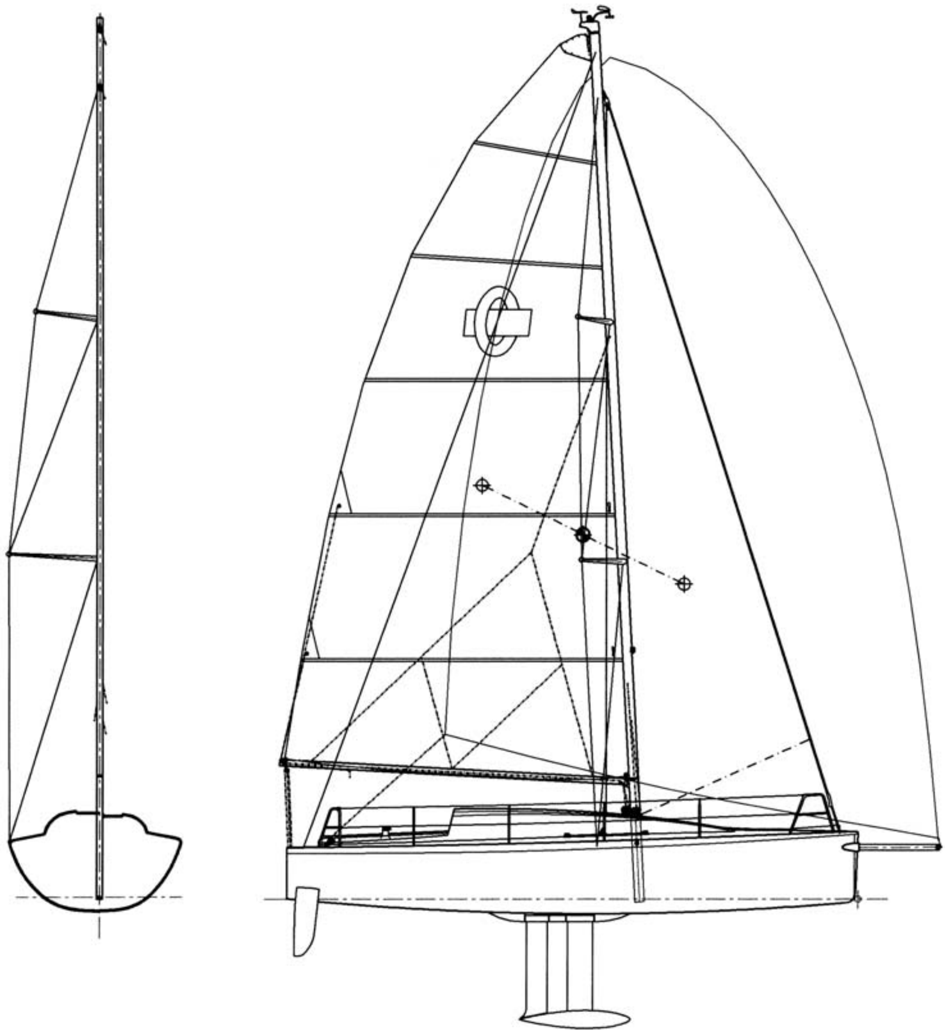

Figure 1: Rig and sail plan

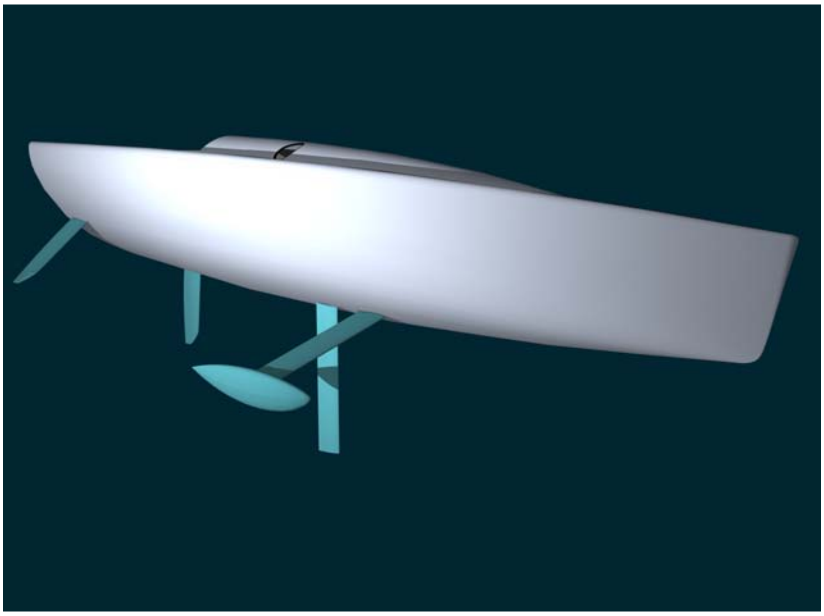

Figure 2: X-keel arrangement

Figure 1 shows the sail and rig plan. The „sailOvation" has a 9/10 fractional rig with two 25° aft raked spreaders, no backstay and no checkstay for easy handling as a cruiser. The absence of a backstay enables a big roach of the main sail and a low centre of effort. The rig has top runners. For this type of rig the runners are only used for controlling the mast bend and as a mast support when running [1].

The main dimensions of the rig are:

P = 11.760 m	I = 11.960 m
E = 5.420 m	J = 3.160 m.

The main sail has an area of 42 m². It is fully battened and has a big roach for high efficiency. The genoa has an area of 21 m². It has a furler for easy handling. There is no spinnaker but a gennaker with an area of 90 m². The sails were sponsored by elvstrom sobstad.

The rig is constructed by Nordic Mast with a carbon mast tube and after some trouble with aluminium spreaders also carbon spreaders. The use of carbon instead of aluminium reduces the weight of the rig. An aluminium mast tube weighs about 50 % of the whole rig weight. A carbon mast tube weighs again about 50 % of an aluminium mast tube. The weight reduction for the complete rig is accordingly about 25 % choosing carbon for the mast tube instead of aluminium. Carbon for mast tubes is common on racing yachts today and there was no other choice for the "sailOvation" than to choose carbon.

On the search for more weight reduction in the rig there was a look at the shrouds, commonly made out of wire for cruisers and rod for racers. SmartRigging delivered the shrouds for the rig. They are not out of nitronic rod but produced out of PBO-HM (p-phenylene-2,6-benzobisoxazole). That is a new high performance fibre developed by TOYOBO. HM means High Modulus. PBO is still new for the rigging of sailing yachts. Classification companies like the Germanische Lloyd develop Guidelines for type-approvals [2]. PBO is also called Zylon. It has superior tensile strength, elasticity modulus and creep properties than aramid fibres. PBO is suitable for shrouds for it does not creep as much as aramid fibres. The fibres (1.5 denier) have a tensile strength of

5,800 MPa and a tensile modulus of 280 GPa. The density is 1.56 g/cm³. PBO needs a protection cover for it disintegrates after being exposed to sunlight for only a few days, it can chafe and water absorption should be avoided. End terminals for fibre cables have always been a problem. The shrouds of the “sailOvation” are constructed in winding endless fibres round both end fittings. The end fittings are cast in a sturdy poly urethane coating. The custom made PBO shrouds have to be pre stretched with high tension forces to receive their mechanical properties.
The PBO sizes for the standing rigging of the “sailOvation” are not chosen by the equivalent strength but by the equivalent stiffness of rod. The equivalent stiffness is the product of the modulus of elasticity and the cross section area. It should be the same for PBO and rod to get the same stiffness for the rig. The strength of PBO is, when choosing the same stiffness, bigger than that of rod. PBO cables weigh about only one fourth to one third compared to cables out of rod but the diameters of PBO are about 50 % bigger. **Table 1** shows a comparison between rod and PBO for the shrouds of the “sailOvation” neglecting the different terminal weights. The head stay is not changed from rod to PBO to be able to mount a furler and the runners are out of vectran.

Table 1: Comparison between Rod and PBO for the transverse standing rigging of the “sailOvation”

		Rod				**PBO**			
shroud	length	D	mass/length	mass	area	D	mass/length	mass	area
V1	4.741	6.35	250	1,185	0,030	9,5	80	379	0.045
V2	3.890	5.03	157	611	0,020	7,5	60	233	0.029
D1	4.729	5.03	157	742	0,024	7,5	60	284	0.035
D2	4.053	4.37	118	478	0,018	6,5	50	203	0.026
D3	3.626	5.03	157	569	0,018	7,5	60	218	0.027
	m	mm	g/m	g	m²	mm	g/m	g	m²
			total Rod:	**3,586**	**0.109**		**total PBO:**	**1,317**	**0.163**

The weight of the rigging of the “sailOvation” is reduced by 2.269 kg choosing PBO instead of rod. The PBO rigging has 63 % less mass but 49 % more windage than the rod rigging. The weight reduction of 2.269 kg does not look to be very much on the first view. But the centre of gravity of the rigging is at about 45 % of the height of the mast top. Using PBO instead of rod leads either to bigger righting moments or allows - keeping the righting moment constant - a reduction of the bulb weight of about 3 times of the weight reduction in the rigging. That would be all together 9 kg less weight for the whole yacht. The decision for PBO moves the centre of gravity of the “sailOvation” 60 mm downwards. The righting moment becomes 4 % higher and raises the propulsion force accordingly - one step more to achieve semi-planing on a close reach.

3. Modelling the rig with finite elements

Rigs of sailing yachts are very complicated mechanical structures. They are three dimensional and made of long slim elements. The elements have either 3D bending characteristics of beams (mast, spreaders and boom) or tension only characteristic of cables (shrouds, stays). Cables are non linear elements for they fall slack when compressed. Rigs are pre tensioned like a screw joint but much more complicated three dimensional. Rigs can become instable. They can buckle caused by compression loads acting on the beams. The beams may buckle as a whole. But also the local wall of the beams can buckle. The loading of the rig changes with the deformation of the rig. This is another non linearity called large deformations and has to be considered for the loading becomes bigger with raising deformations. Loadings are caused by the sails depending on wind speeds, apparent wind angles and sail shape. Sail loads depend also on sail trim like mast bend and head stay sag. Sail trim depends again on the deformations of the rig which are caused by the sail loading. And last but not least there are also loadings by inertia forces in a sea way.

When in engineering work something is as complicated as the structure of a rig, a useful way is to combine some simple physics like the Euler buckling formula for beams with a lot of experience and reserve factors. Most spar fabricators go this way and develop their own spread sheets for dimensioning rigs to get numbers for the necessary diameters of standing rigging or moments of inertia for the mast. This way is easy, reproducible and quick. Rules like the Nordic Boat Standard [3] are also based on this procedure.

But if you want to optimize a rig with regard to weight and deformations you have a problem. A spread sheet for rig dimensioning is not an analysis of the rig structure. The spread sheets can't compute deformations or tensions of the rig and it components. You have to choose a more sophisticated "high tech" computation called FEA (**F**inite **E**lement **A**nalysis). Only FEA helps to understand the behaviour of rigs and enables to optimize them.

FEA for rigs is not new. There are several publications [4 – 9] which describe the successful use of FEA for rigs. The Germanische Lloyd has published guidelines [10] for the certification of large modern rigs that are based on FEA.

Important aspects for the simulation of the rig of the "sailOvation" with finite elements are:

- **geometry:** 3D including mast rake, lift and rake of spreaders, load points like halyard sheaves axles
- **elements:** 3D beams for mast, spreaders and boom; nonlinear link elements with the ability to fall slack when compressed for the shrouds, beam elements for the head stay to make visible the sag; bearing element for goose neck of the boom; spring element at the chain plate of the head stay to simulate the hull stiffness
- **real constants:** cross section areas, moments of inertia according to the carbon spars and PBO rigging
- **material properties:** according to laminate plan for carbon, PBO, rod and vectran
- simulation of the **real connecting points** of the elements for example between mast and spreader or tang of a shroud with so called "helping beams" from the centre line of the mast to the outside of the mast tube
- **constraints:** the hull is not modelled, clamping of key points at the connections to the hull like chain plates and mast step, all in x, y, z direction and mast step additional in zz
- consideration of geometrical non linearity, **large deformations**

The computations for the "sailOvation" are performed with the software ANSYS on a PC. The geometry of the modelled rig can be seen in **figure 3**.

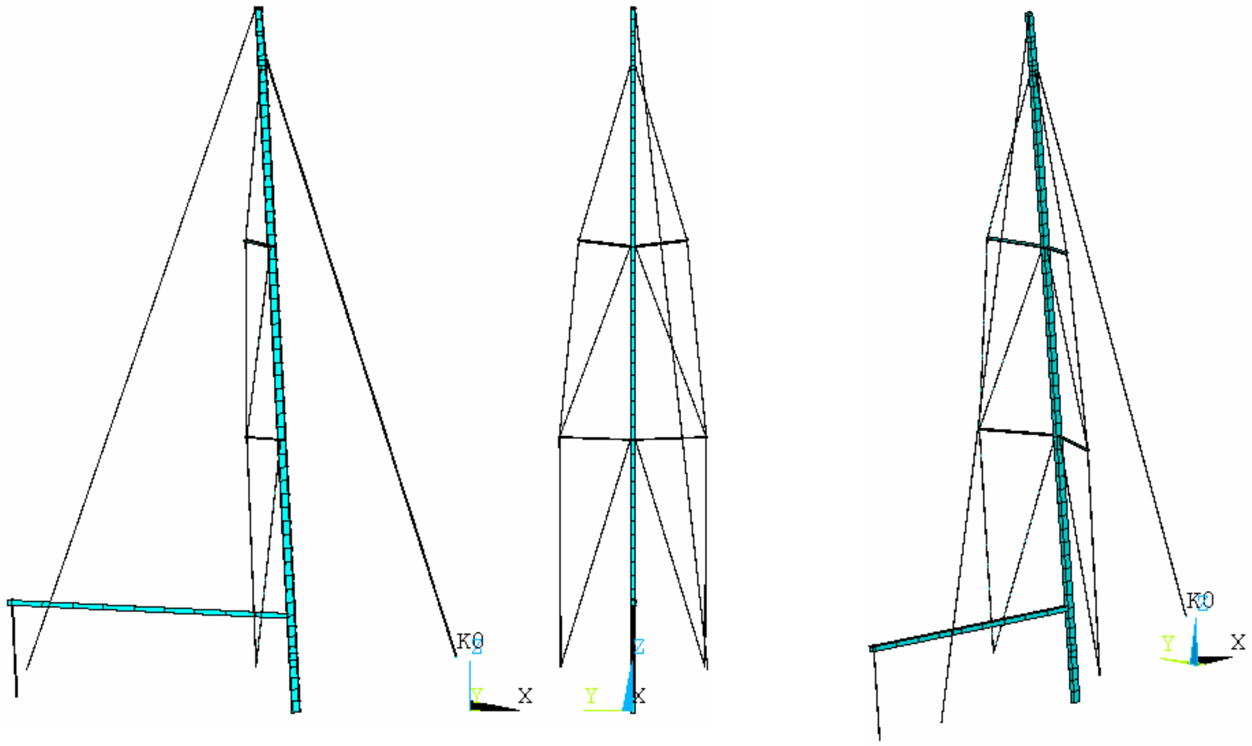

Figure 3: Geometry of FE model, looking from starboard side, astern and 3D

4. Pretensions

There are different ways to tension the standing rigging. To tension it intuitive and adjusting it on the leeward side when sailing may lead to acceptable results only for simple cruising sailboat rigs. A second and more exact method is to measure the elongations of the standing rigging as a percentage of the breaking loads. Typical tension loads are 15 to 20 (25) % of the breaking loads. A limiting factor is, that it may be impossible to achieve the necessary tensions by turning the rigging screws with hand tools. The threads of the rigging screws may also be damaged in the procedure. The third way is to use a hydraulic jack. The principle use of a hydraulic jack is to adjust the rigging screws without tension loads on them and then to lift the mast step with the jack and to set it on shims. Good pretensions can be achieved with some iteration on the length of the rigging screws. This method is much more certain and reliable than the other ones mentioned above. The pretensions of a rig become reproducible. That is very important for racing rigs with different pretensions for different wind speeds and seaways. Hydraulic jacks are today common on racing yachts with a length of 10 m and more. The knowledge about the size of the pretension forces in numbers in the rigging is unfortunately very limited unless there are load cells at the chain plates. This can be changed by using FEA for the rig.

The procedure of tensioning the rig of the “sailOvation” with a hydraulic jack is simulated with FEA. With a FEA the shrouds can be shortened using a function called “initial strain”. To find the right “initial strains” for every shroud and the head stay is an iteration process like in “real live”. It takes some time with FEA especially for rigs with aft swept spreaders. The reason is the interaction between fore/aft and transverse rigging. Four conditions have to be complied. First the mast shall have a pre bend in the dock tune of 0.5 % of the P measurement. Second the head stay sag, when sailing close hauled with 25° heel, must be small. Sag of 1 % of the forestay length is common on racing yachts to get an effective headsail. Third the cap shrouds are not allowed to fall slack (the D's may fall slack) when sailing close hauled with 25° heel. Otherwise the rig will start to collapse. And fourth the rig has to be able to carry the sail loads without buckling of the mast. The sail loads correspond with the righting moment at 25° heel. The fourth condition may be not fulfilled, when the rig is not stiff enough.

To come back from simulation to "real live" there has to be a way to achieve the computed "initial strains" in the real rig. The way is to subdivide the dock tuning into three steps:

1. tensioning only the cap shrouds (V1, V2, D3) and the head stay,
2. tensioning additional the D1's and
3. tensioning additional the D2's.

For every step the compression forces in the mast foot are computed with FEA and listed in table 2.

Table 2: Jacking up the rig in three steps

step	tension in	hydraulic pressure [bar]	force in mast foot [kN]
1	V1, V2, D3, headstay	75	9,8
2	additional D1	266	34,5
3	additional D2	322	41,9

Now the simulated steps have to be transferred to the real rig. In the first step in "real live" the rigging screws of the V1's and the head stay are iteratively adjusted until the compression force (corresponding with the hydraulic pressure, which could be controlled by a pressure gauge) of the computed first step is achieved. In the second step the D1's are adjusted until the computed compression force for the second step is achieved. The same procedure is performed with the D'2s in the third step.

Figure 4 shows the computed forces and the deformations of the rig for every step. The forces in Newton [N] are made visible with contours and colours. The width of the contour is proportional to the force. The mast bending curve is shown with vectors in meter [m]. The length of the vectors and the colour correspond with the deformation in three dimensions. The length of the vectors is in an enlarged scale to make the small deformations visible.

It is of great importance, that the computations are performed with the non linearity of large deformations. In the first step the mast bends forward a lot by the compression forces of the spreaders. The mast top moves downward. In the second and third step the mast is pulled back by the D1's and the D2's and straightened to the 0.5 % pre bend. The straightening of the mast tensions the cap shrouds for the mast top moves up again. Neglecting large deformations (here specially the bending deformation of the mast) leads to wrong tensions. The cap shrouds would be tensioned too much in the first step.

Hydraulic jacks can produce a lot of force and may overload the rig when used carelessly. It is good engineering to control the stress levels in the rig for the three computed steps jacking up the rig.

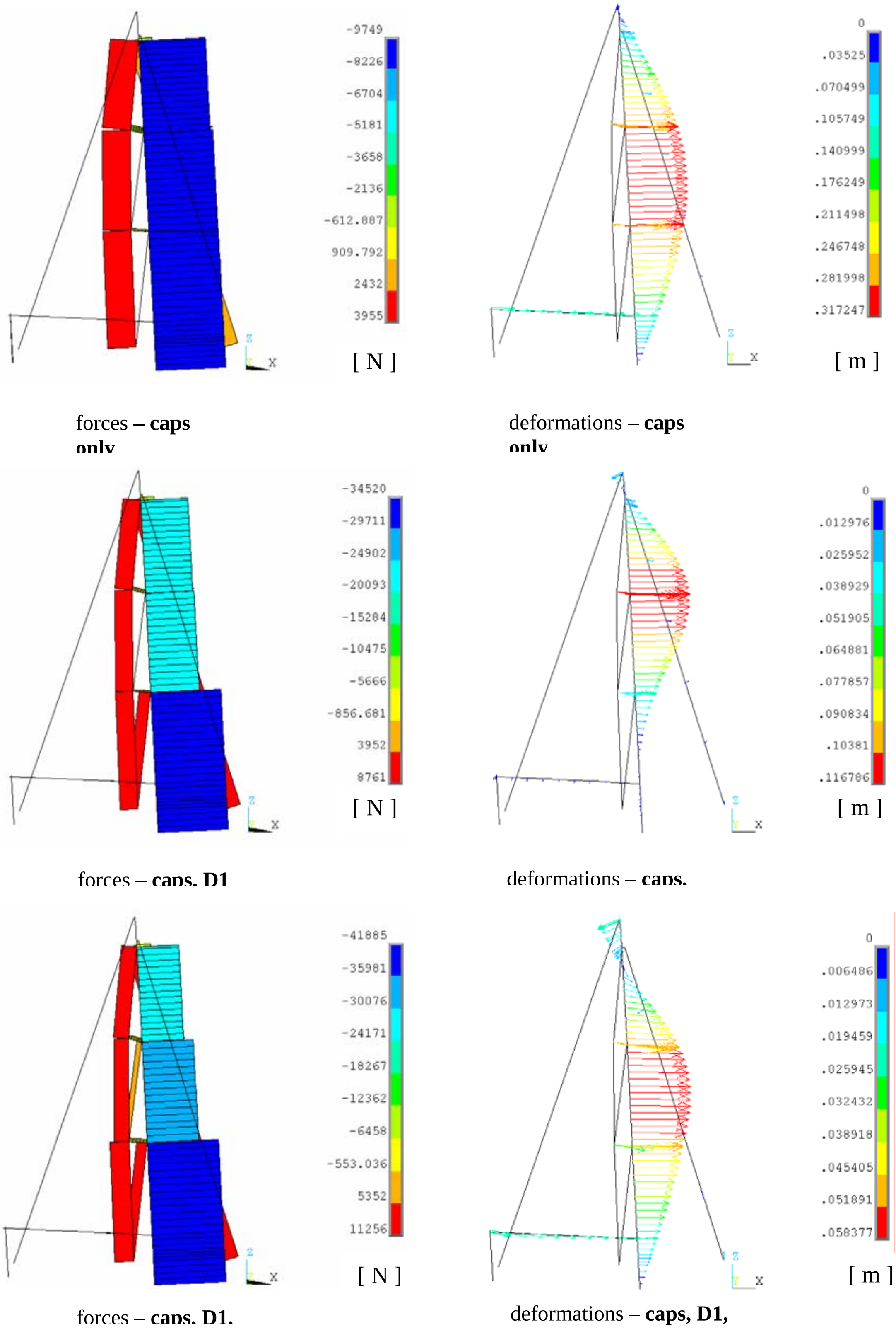

Figure 4: Forces and deformations jacking up the mast with a hydraulic jack in three steps

5. Sailing close hauled

The forces on the rig sailing close hauled depend on the righting moment. Computations were performed for the righting moments corresponding up to 25° heel with the keel fully canted to windward. The righting moment at 25° heel is 2,750 kgm. The wind in the computations comes from the starboard side.

Forces and line loads acting on the rig are computed on the base of a load model developed by full scale measurements of rigging loads and FEA on the research sailing yacht "DYNA" of the TU-Berlin [5]. **Table 3** shows the forces and line loads for a righting moment of 2,670 kgm. This is the maximal possible righting moment for a mast pre bend of 0.5 % of the P measurement. Computations with higher righting moments did not converge, what means, that the rig in the computations is buckling under the pretension and sail loads. In real live the mast does not buckle completely. The mast helps itself by bending much and this automatically depowers the sails, reducing the sail loads on the rig. The applied forces of the sails in the FEA are independent of the mast bending and the sag of the head sail. The sails always stay full in the computations. This way the computations show the limit of the rig to carry the full power of the sails according to the righting moment of the hull.

A pre bend of 0.5 % of the P measurement is a good standard value. FEA showed, that smaller pre bends allow higher sail loads than bigger pre bends. The reason for this is the different stiffness of the rig. An almost straight mast is stiffer than a mast which is already bent a lot. A less stiff mast has also less tension forces in the head stay. This leads to larger sag of the head stay and poorer performance of the genoa. A complete straight mast would be best for stiffness. But when there is no or a too small pre bend in the mast movements in a seaway like pitching results in inverting and pumping of the rig. This has to be avoided by pre bending the rig a little bit and the 0.5 % pre bend is a good compromise between stiffness and avoiding inverting and pumping of the rig (see also chapter 6).

Table 3: Forces and line loads acting on the rig sailing close hauled with a righting moment of 2,670 kgm

Forces		Main sail	Genoa	
halyard sheeves	x	-1554	92	N
	y	430	203	N
	z	-7621	-4062	N
boom end, outhaul	x	3201		N
	y	678		N
	z	4103		N
gooseneck boom	x	-402		N
	y	203		N
	z	101		N
Line loads		constant on mast	triangle on fore stay	
x		-140	-247	N/m
y		81	143	N/m

The computed forces, deformations, bending and torsion moments can be found in **figure 5**. The compression force in the mast step raises from 41,885 N for dock tuning to 49,350 N when sailing close hauled. The leeward shrouds are almost slack. The runner is not tensioned. The mast top has a deformation of 267 mm. The sag of the head stay is 94 mm or 0.76 %. That is less than 1 % and a very good value.

The biggest bending moment is 3,163 Nm in the top of the mast at the head stay tang. The halyard of the mainsail pulls at his sheave the mast top backwards. This results in steadily raising bending moments starting from the mast top downwards to the head stay tang. Here counteracting moments from the forestay forces and the halyard forces of the genoa reduce the bending moment with a jump in the bending moment curve. Torsion moments increase from the masthead stepwise with every tang and spreader. They are relatively small.

Figure 6 shows a strength control in the carbon mast with von Mises stress. The biggest value of 180 N/mm² can be found on the leeward aft side of the mast in the height of the forestay tang. This corresponds with the location of the biggest bending moment. At this location there are additional local reinforcements not considered in the global FEA model. The real stresses are smaller. This part of the mast should be evaluated further with a local FEA model.

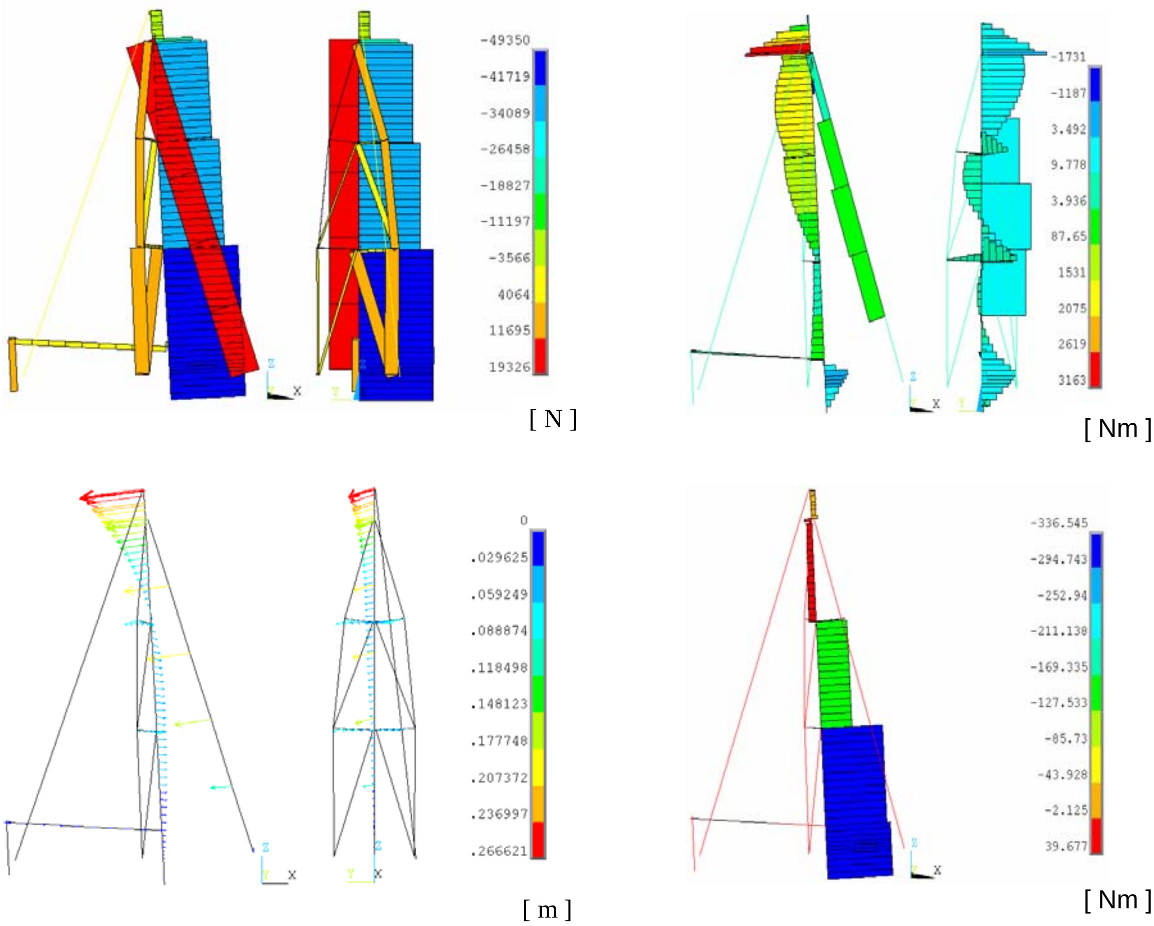

Figure 5: Sailing close hauled: forces, deformations left side – bending and torsion moments right side

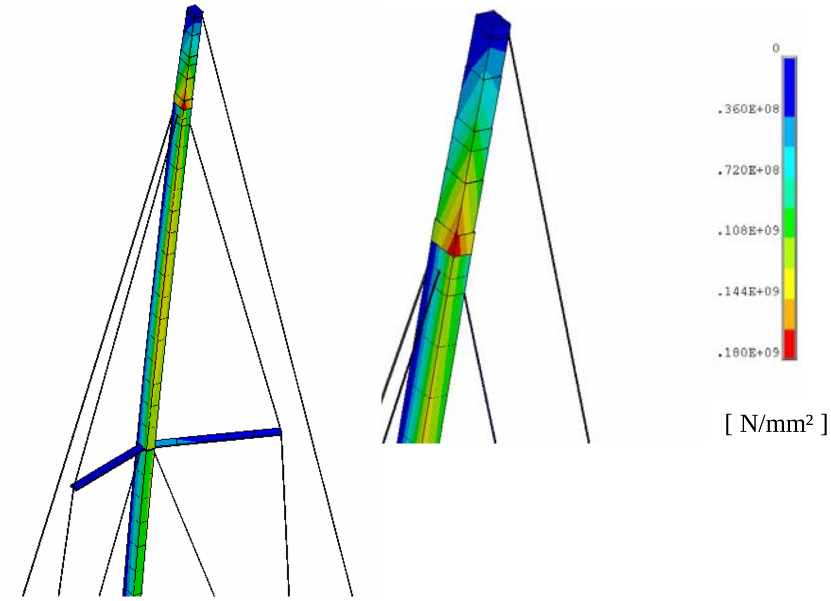

Figure 6: Von Mises stress looking from port side

6. Validation of trial runs, applicability of FEA for rigs

First trial runs started in the summer 2006. The rig was pre tensioned according to the described procedure in three steps on the base of the FEA. The achieved mast compression in the last step corresponded very well with the computed one. The procedure to pretension the rig this way worked very well. It took less than one hour and was very satisfying.

Different pre bends of the mast in the dock tune were examined. First sailing trials with a pre bend of the mast in the size of 0.1 to 0.2 % of the P measurement were disappointing. The rig in this dock tune is very stiff and able to carry a lot of sail power, but the mast started to invert and to pump sailing in a seaway. A pre bend of 0.5 % proved to be enough to avoid inverting of the mast and the rig was still stiff enough to carry the sail loads and the sag of the head stay was very small like computed with FEA.

Higher pre bends of the mast were also examined. The luff curve of the main sail was very rounded and with the almost straight mast the sail chord depth was too big. It was tried to bend the mast round the main sail luff to reduce the chord depth. The tensions in the diagonals (D1's, D2's) were reduced and the mast pre bend in the dock tune was raised up to 2 %. The main sail could now be trimmed very well and the sail chord depth could be adjusted by bending the mast with the runner. But there was a very negative effect for the genoa. The sag of the head stay became too big sailing close hauled. Pulling at the runner only worsened the sag of the head stay. The rig is not stiff enough with 2 % pre bend of the mast. It has already started to buckle. There is no alternative, a new flatter main sail with a less rounded luff is necessary for the rig of the "sailOvation".

Results of FEA performed with different pre bends are in accordance with the results of the sail trials. The pre bend of the “sailOvation” mast has to be small to get a stiff rig. Otherwise the sag of the head stay becomes too big. The sail maker can design his sails much better, if he knows exactly the deformation behavior of the rig. The deformation behavior can be computed with FEA and need not be tested expensively with sets of sails with different luff curves.

The experiences with FEA for the rig of the “sailOvation” are:

- FEA is applicable for rigs very well
- the results of the FEA correspond very well with the experiences in the real world
- FEA helps to understand the structural behavior of rigs
- using FEA for a rig reduces time for trial runs and saves costs.

To perform a FEA for a rig you need a good computer, powerful FEA software and a qualified engineer. FEA is a common tool in the automobile and aircraft industries to optimize structures and to reduce costs. But FEA for rigs is until today only seldom performed. Mast builder usually use self made spreadsheets and experience to dimension the mast tube and the standing rigging. Some sparmakers don’t do any calculation at all to cut costs. Until customers are prepared to pay a proper price for FEA it won’t happen more often. A customer is willing to pay a lot of money for carbon and the combined high tech feeling but not for computations that he cannot understand. Even with full global FEA the rig can fall down. Most errors are in fact associated with fittings and attachments. Global specifications of mast stiffness and rigging sizes are seldom the fault. Local FEA of all that fittings and attachments is an order of magnitude beyond the global FEA. The reasons for sparmakers to go without FEA for rigs are mainly costs but also lacking FEA know how. The costs for a global FEA are almost independent of the size of the rig. For small rigs the percentage of the total costs is prohibitive high. For large rigs, that cost several hundred thousand Euros, a FEA is only a small part in the bill. That is the reason why a FEA is almost only performed for large rigs.

The costs of FEA for rigs are accepted by the customer only when he gets advantages. The advantages are:

- insurance companies **reduce** their **premiums** if a rig is certified for example by the Germanische Lloyd according to his guidelines that are based on 3D FEA computations [10]
- **quickly, reproducible and defined dock tuning** in steps with a hydraulic jack on the base of computed hydraulic pressures
- **optimization** of the behaviour **of the rig** before it is built; much less expensive changes after trial runs with bad results
- data for the deformations of a rig under sail and trim loads like bending curves of the mast and the sag of the head stay; this **data** are important **for the sailmaker**
- **safe weight reduction:** global stress control of the mast tube, the spreaders, the boom and the standing rigging; dimensions of cross sections can be adjusted so that they are safe and not unnecessary heavy
- **3D buckling control** of the rig by computing with large deformations and simulating the buckling process with raising sail loads or alternative and more simple 3D linear “euler buckling”.

The velocity polar diagram of the “sailOvation” can be seen in **figure 7** for a true wind speed of 12 kn. She starts semi-planing (Fn = 0.4) at a wind angle of about 60° on a close reach. The “sailOvation” reacts very sensible to trim changes. She has still a potential for higher velocities in the next summer with a new main sail and a better trim.

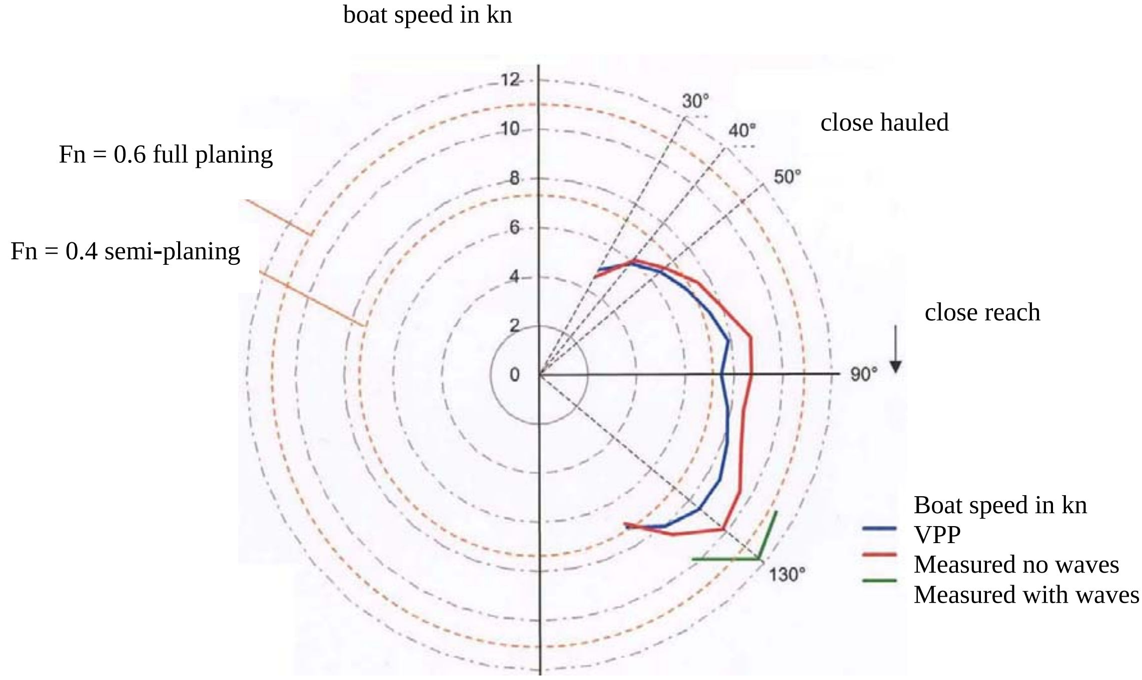

Figure 7: Polares for 12 kn (6 m/s) true wind speed

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