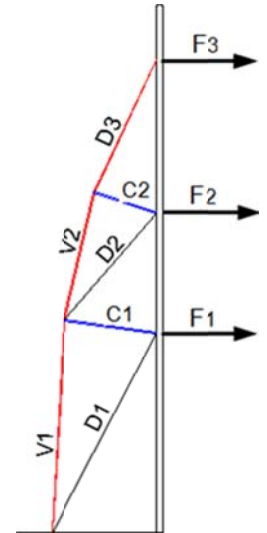


Mast and Rigging

GENERAL

The column mast members are termed panels, and extend between supports such as the spreaders or the deck. The upright stays are the verticals (or V's), while the angled stays are termed diagonals (or D's). The outermost stays (V1, V2 and D3 in Figure 1) usually carry the highest loads, and as a group are termed the cap shrouds. They work in conjunction with the spreaders to provide lateral support to the mast and transmit most of the forces from the sails to the hull. The diagonals often carry smaller loads as they support the middle regions of the mast, helping to carry the lateral load.

The primary role of stays in a rig is to support the mast, working in conjunction with the spreaders. Spreader act as small compression struts whose role is to improve the angle of the stays to the mast. In this way, 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.



Typically, stays are made of wire or thin rod and have very low bending “stiffness”, such that they will sag under their own weight.

All intersections between stays and spreaders are designed to allow swivel movements, so that the platform can be modeled as a structure with articulated joints.

For sizing the rest of the rig, mast and rigging windward is considered a statically determinate structure. The heeling moment at deck level is the result of forces acting on the ball joints between the panels and spreaders. The forces distributed from the main sail and the forces acting between panels must be translated to the forces acting on the bearings as shown in Figure 1. The equilibrium equations can determine the forces on the shrouds and forces on the panels and thus the required dimensions.

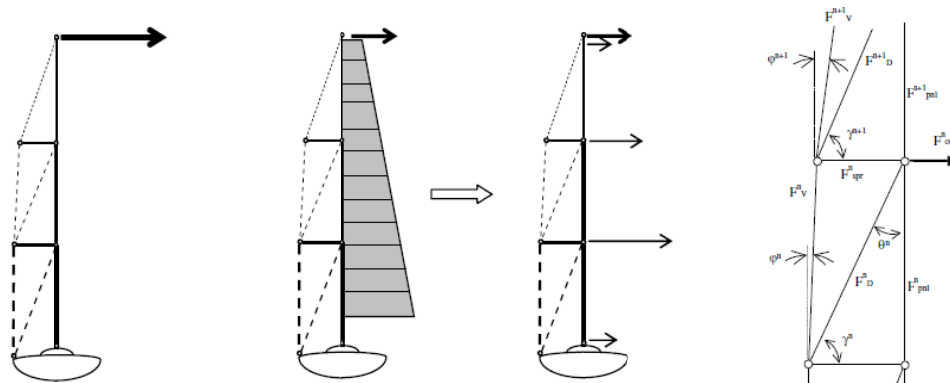


fig.1

Because this approach is not possible to examine, for example, local buckling or the effects of variations in the initial charge, interactions due to the spacers, the fore and aft stays, bridges, etc. Nor is it possible to determine, for example, the general behavior of the rig and bending deformation under normal conditions of navigation.

It would need a nonlinear analysis of a three-dimensional model to do so.

The forces generated by a velocities prediction program are translated, by a computer program, to forces acting on the rig.

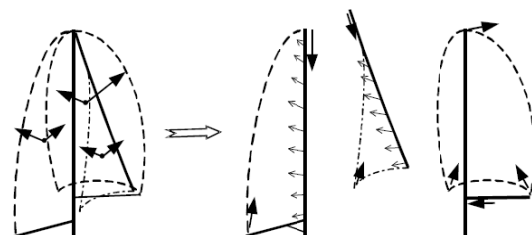


fig.2

METHODS FOR STUDY OF RIGGING

Although there are other methods, we will only talk about two of them, the method of Skene and NBS (Nordic Boat Standard), but the program will calculate according to the NBS.

Skene's Method

The starting point of this method is the transverse stability of the vessel expressed in terms of righting moment.

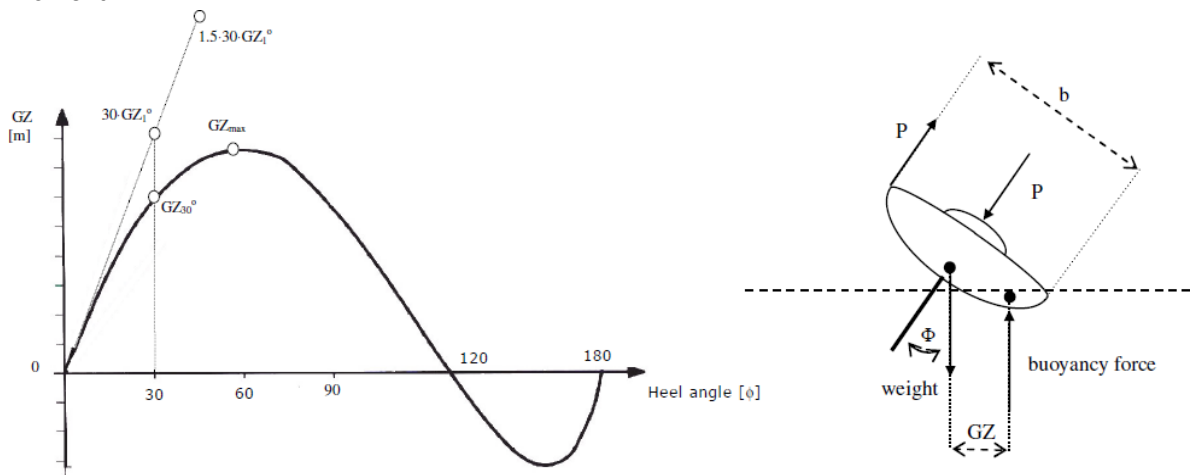


fig.3

Based on the stability at 30 ° Skene's method estimates the maximum compressive force on the mast, by the following formula:

$$P = 1.85 \cdot \frac{1.5 \cdot GZ_{30^\circ} \cdot \Delta \cdot g}{b/2} = 1.85 \cdot \frac{1.5 \cdot RM_{30^\circ}}{b/2}$$

P = compression force on the mast [N]
 Δ = ship's displacement [kg]
 g = acceleration of gravity [m/s²]
 b = width between clamping plates [m]
 GZ_{30° = righting arm at 30° [m]
 RM_{30° = righting moment at 30° [Nm]
 1.5 = factor to take into account heeling angles over 30°
 1.85 = coefficient by loads of stays, shrouds and halyards

In general the designer of the mast does not know the initial stability but it can meet the heel stability at 1°. In that case, the value is multiplied by 30, assuming that the righting arm GZ curve closely resembles a straight line. As shown in Figure 1, this value ($30 \cdot GZ_{1^\circ}$) may be greater than the GZ_{30° .

The formula represents the equilibrium in the transverse direction. The assumption is that the leeward shrouds are relaxed at this angle of heel.

The maximum compression force on the lower panel of the mast and the tensile force in the windward stay, both equal in magnitude, are used to determine the required dimensions of the stay and the flexural rigidity (EI) of the panel, both the transverse and longitudinal direction. The general method for the flexural stiffness is to use the formula of Euler buckling. Distinction must be made between the transverse and longitudinal, due to the different lengths of the supports

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{k^2 \cdot L^2}$$

$$E \cdot I = \frac{k^2 \cdot P_{cr} \cdot L^2}{\pi^2}$$

P_{cr} = critical buckling load for the panel [N]
 E = elastic module of the panel [pa]
 I = moment of inertia in transverse or longitudinal direction [m⁴]
 L = panel length between supports [m]
 k = factor depending on the type of support

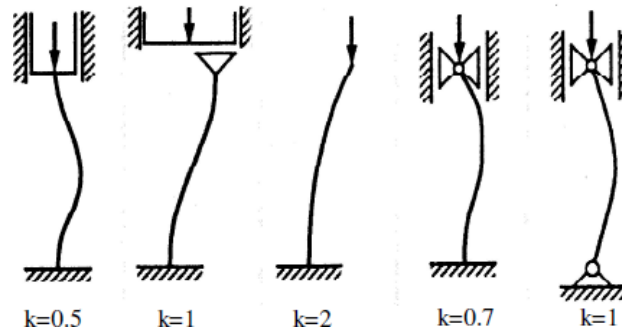


fig.4

NBS (Nordic Boats Standard) METHOD

First NBS begins with the description of the type of vessels to which the method is applicable; *small boats of less than 15 m in length, with an jib area of less than 1.6 times the area of the mainsail.*

Second NBS establishes the nomenclature according to the type of rig, depending on the number of spreaders (if any) and if the shrouds are fixed to the masthead or not.

F : Fractional Rig

M : Masthead Rig

-0, -1, -2 : Number of spreaders

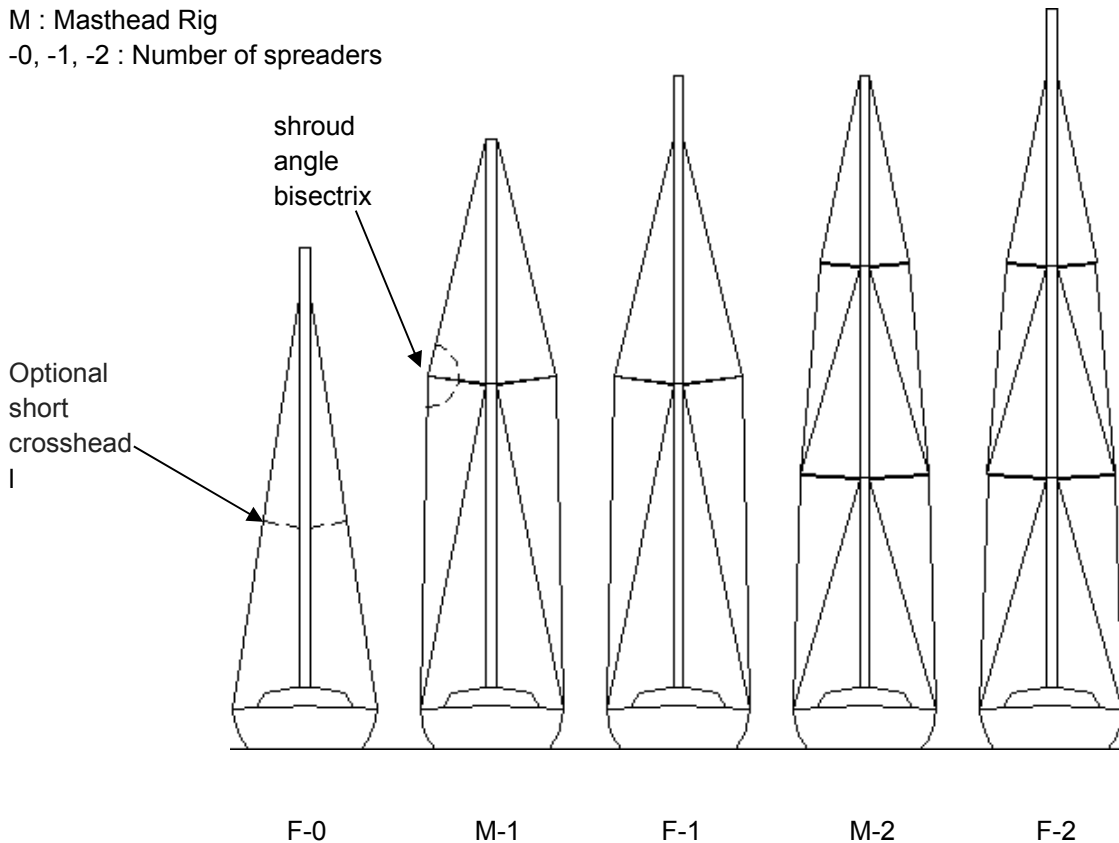


fig. 5

The outline of the method is as follows:

- Determine the righting moment due to the shapes of the hull at 30° heeling
- Identification of the type of rig in accordance with the drawings and nomenclature (see fig.5).
- Apply the equations to determine the moment of inertia necessary

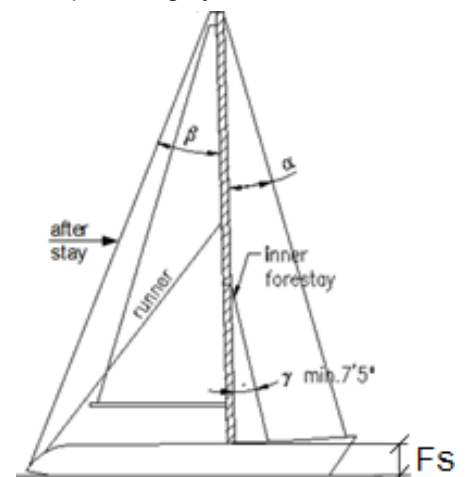
The righting moment is to be calculated including crew action. Consider that in navigation the function of the crew "by band" is very important. The NBS provides a way to calculate quite roughly what the momentum created by this crew "by band":

$$\delta_{RM} = 75 \cdot n \cdot (3.4 \cdot B - 4.9 \cdot F_s)$$

Where **n** is the number of crew, **B** the breadth of the sailboat and **FS** freeboard in the vicinity of the mast.

This gives us the righting moment induced by the crew. The righting moment that will be used throughout the entire design is the sum of the moment at 30° due to hull forms plus the one created by the crew.

$$RM = RM_{30} \cdot \text{Displacement} + \delta_{RM}$$



The next step is to begin to scale the mast transversely.

Although this is a three-dimensional structure, in order to provide a point of simplicity when sizing, it tends to make separate studies for its transverse and longitudinal behavior.

The stability of the mast transversely depends on the number of spreaders and mast foot placement, which may be supported on deck or resting on the keel.

The longitudinal stability also depends on the mast foot placement, the number of spreaders and their placement (delayed or perpendicular) and the stresses applied to the stays and shrouds.

The forces applied come from the wind pressure exerted on sails and dynamic forces created by wind and sea. Here they are considered two different load cases:

- In the first case the rig is loaded only by the action of wind on the headsail.
- In the second case the rig is loaded by a deep reefed main sail (very harsh weather conditions are assumed).

First Case : The transverse force is independent of the shape of the sail to be used and will be simply the righting moment divided by the distance between the water line and where is fixed the forestay to the mast.

$$T_1 = RM/a_1$$

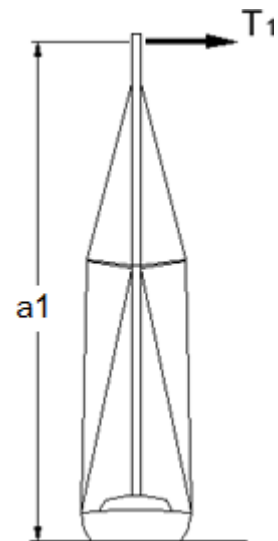


fig.6

Second case : The transverse force in this case is also obtained by dividing the righting moment by the distance between the water line and the center of pressure of the main sail (approximately 1/3 of the height of the candle from the boom) .

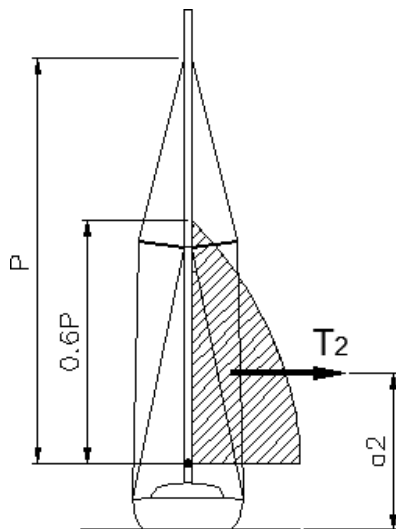


fig.7

$$T_2 = RM/a_2$$

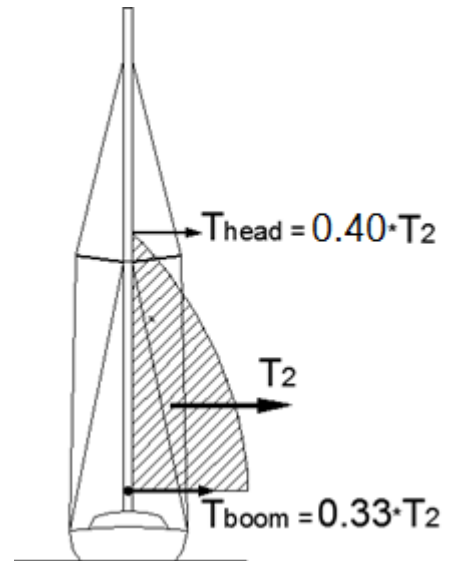


fig.8

This force (T_2) is then decomposed into two forces, one applied to the top of the sail (T_{head}) and another applied to the boom (T_{boom}).

These two forces (T_{head} and T_{boom}) In turn can be decomposed into two.

The load of the stop of sail can be distributed among the crosshead that is below and the crosshead or cap shrouds it has left over.

$$T_{hu} = T_{head} * d1/(d1+d2)$$

$$T_{hl} = T_{head} * d2/(d1+d2)$$

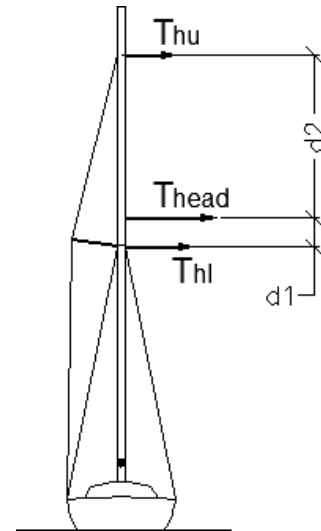


fig.9

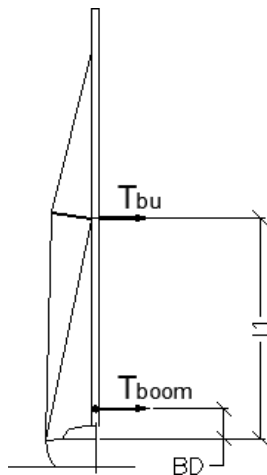


fig.10

The load of the boom is also distributed between the deck and the first floor of spreaders.

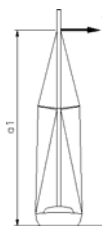
Want to know the loads on the first floor of spreaders and get as a fraction of the strength of the boom proportional factor between the height of the boom relative to the deck and the height of the spreader relative to the deck.

$$T_{bu} = T_{boom} * BD/l_1$$

Now we have the transverse forces acting on the structure. Depending on the configuration chosen is obtained, for example, the set of forces that fig.11 shows.

As for the first load case:

$$F1 = F2 = 0 \quad F3 = T1$$



And for the second load case one must differentiate between two situations:

- Situation A:

the end of the sail is above the second floor of spreaders.

$$F1 = T_{bu} \quad F2 = T_{hl} \quad F3 = T_{hu}$$

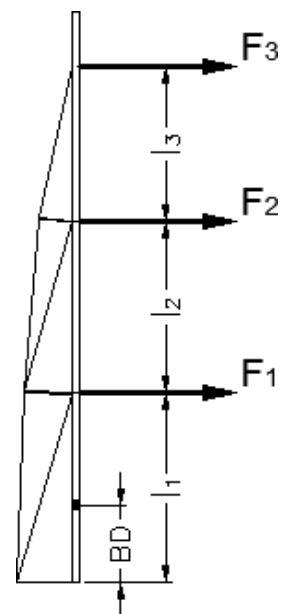
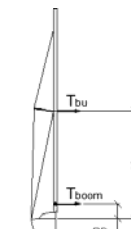
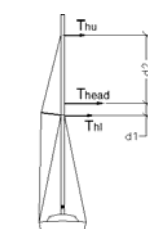


fig.11

- *Situation B:*

the end of the sail is between the first and second floors of spreaders.

$$F1 = Thl + Tbu \quad F2 = Thu \quad F3 = 0$$

When we calculate the stresses in the shrouds have to consider the two load situations separately (load only the headsail and loading only the main).

We compare the results and choose the one that is worse for the structure, for example, be used for each shroud the greatest load is obtained by comparing the two cases.

The determination of the stresses in the shrouds is made by resolution of forces as shown in fig.12

Tensions in the shrouds if a 2 spreaders case :
(assuming horizontal spreaders, for simplicity)

$$\begin{aligned} \text{Node 6 : } D_3 \cdot \sin \beta_3 &= F_3 \\ \text{Node 5 : } V_2 \cdot \cos \gamma_2 &= D_3 \cdot \cos \beta_3 \\ C_2 &= D_3 \cdot \sin \beta_3 - V_2 \cdot \sin \gamma_2 \\ \text{Node 4 : } D_2 \cdot \sin \beta_2 &= F_2 - C_2 \\ \text{Node 3 : } V_1 \cdot \cos \gamma_1 &= D_2 \cdot \cos \beta_2 + V_2 \cos \gamma_2 \\ C_1 &= V_2 \cdot \sin \gamma_2 + D_2 \cdot \sin \beta_2 - V_1 \cdot \sin \gamma_1 \\ \text{Node 2 : } D_1 \cdot \sin \beta_1 &= F_1 - C_1 \end{aligned}$$

Once calculated tension in the shrouds, given a safety factor, we obtain the design stresses for shrouds.

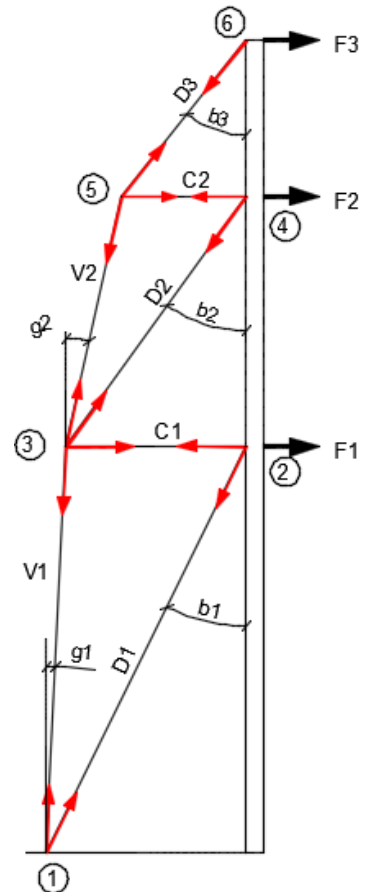


fig.12

These safety factors are directly related to the dynamic loads that are going to be affected due to the structure slamming, wind blows, swings because of the sea state,

Safety factors vary depending on the position occupied by the shroud in question (it stands to reason that does not support the same a shroud working diagonally than one working vertical, or one that works in the lower panel and another who works in upper panel).

Design stresses in shrouds, 2 spreaders case :

$$\begin{aligned} P_{D1} &= 2.8 \cdot D_1 \quad \text{If low single shroud} \\ P_{D1} &= 2.5 \cdot D_1 \quad \text{If low double shroud} \\ P_{D2} &= 2.3 \cdot D_2 \\ P_{D3} &= 3.0 \cdot D_3 \\ P_{V1} &= 3.2 \cdot V_1 \\ P_{V2} &= 3.0 \cdot V_2 \end{aligned}$$

safety factors

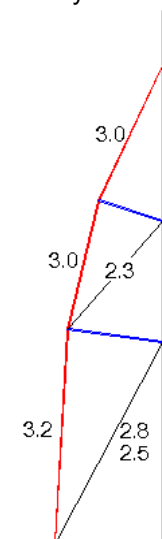


fig.13

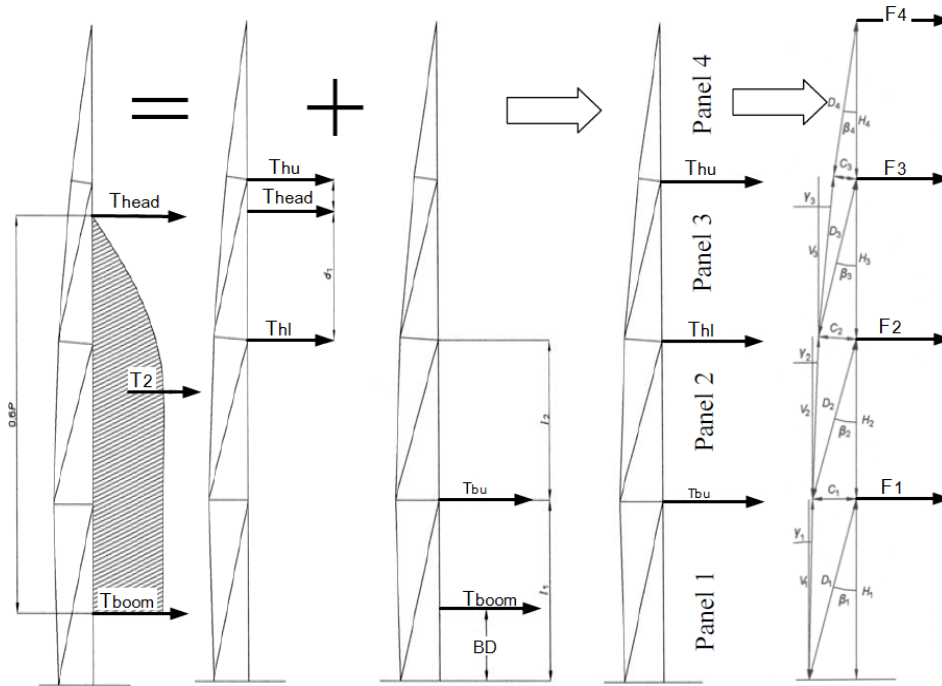


fig. 14 Summary of forces in the case of 3 spreaders

Tensions in the shrouds if 3 spreaders:
(assuming horizontal spreaders, for simplicity)

$$D_4 * \sin \beta_4 = F_4$$

$$V_3 * \cos \gamma_3 = D_4 * \cos \beta_4$$

$$C_3 = D_4 * \sin \beta_4 - V_3 * \sin \gamma_3$$

$$D_3 * \sin \beta_3 = F_3 - C_3$$

$$V_2 * \cos \gamma_2 = D_3 * \sin \beta_3 + V_3 \cos \gamma_3$$

$$C_2 + V_3 * \sin \gamma_3 + D_3 * \sin \beta_3 = V_2 * \sin \gamma_2$$

$$D_2 * \sin \beta_2 + C_2 = F_2$$

$$V_1 * \cos \gamma_1 = D_2 * \cos \beta_2 + V_2 \cos \gamma_2$$

$$C_1 + D_2 * \sin \beta_2 + V_2 * \sin \gamma_2 = V_1 * \sin \gamma_1$$

$$D_1 * \sin \beta_1 + C_1 = F_1$$

Design stresses in shrouds, 3 spreaders case :

$$P_{D1} = 3.0 * D_1 \quad \text{If low single shroud}$$

$$P_{D1} = 2.7 * D_1 \quad \text{If low double shroud}$$

$$P_{D2} = 2.3 * D_2$$

$$P_{D3} = 2.3 * D_3$$

$$P_{D4} = 3.0 * D_4$$

$$P_{V1} = 3.2 * V_1$$

$$P_{V2} = 3.0 * V_2$$

$$P_{V3} = 3.0 * V_3$$

For stays and runners safety factor = 1

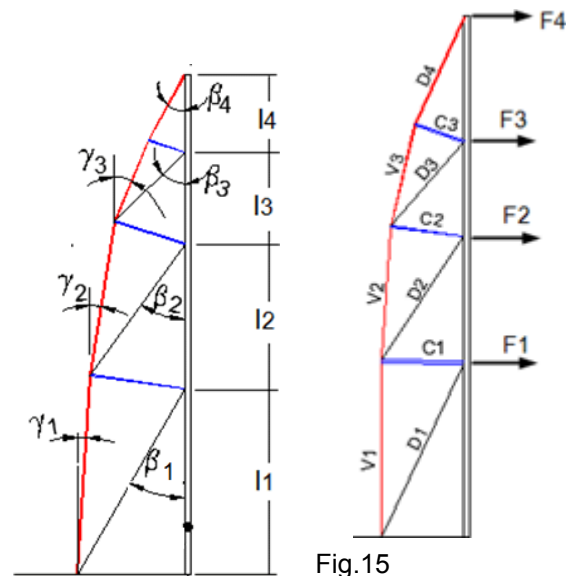


Fig.15



safety factors

The T_{head} is distributed among the crosshead it is below and the one above the top of the mainsail.

In this example, the F_4 would be zero, being the top of the main sail below the 3rd spreader.

If the top of main sail were above the 3rd spreader, the T_{head} be distributed between the masthead and 3rd spreader inversely proportional to their distances from these points

The next step proposed by the NBS is the calculation of the tensions that must endure stays and runners.

The NBS recognizes different cross-sectional configurations. In the case of longitudinal configurations formulation proposed by the NBS it is very similar for all of them, making only a small difference between the masts with forestay masthead and fractionated (forestay below 6% of the length of mast counted from the top).

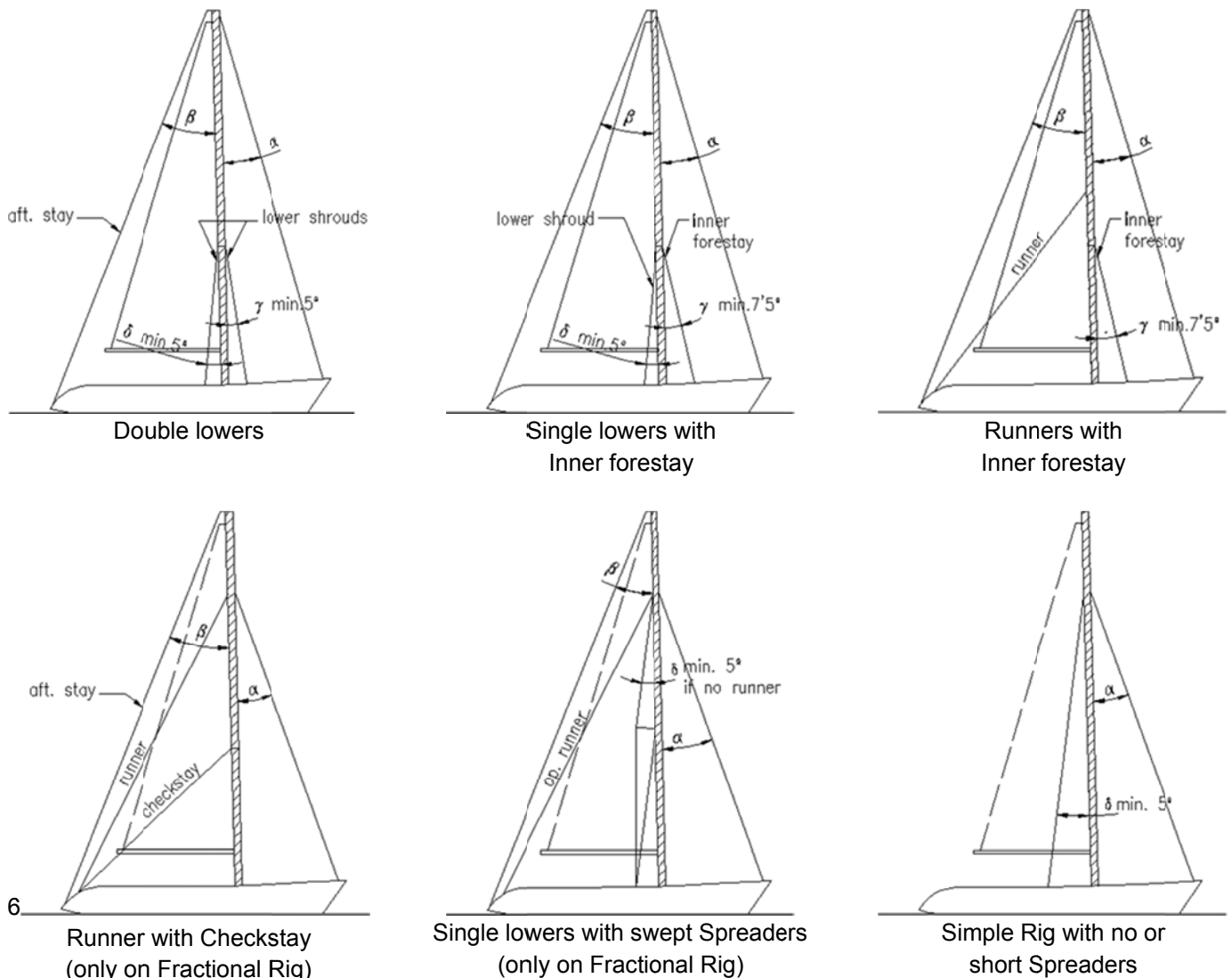


fig.16

The forestay have a tensile strength of at least :

$$P_{fo} = 15 * RM / (l + fs) \quad [N]$$

The inner forestay have a tensile strength of at least :

$$P_{fi} = 12 * RM / (l + fs) \quad [N]$$

The after stay have a tensile strength of at least :

$$P_a = P_{fo} * \sin \alpha / \sin \beta \quad [N] \quad \text{Masthead rigs}$$

$$P_a = 2.8 * RM / (l_a * \sin \beta) \quad [N] \quad \text{Fractional rigs}$$

(these values already include safety factors)

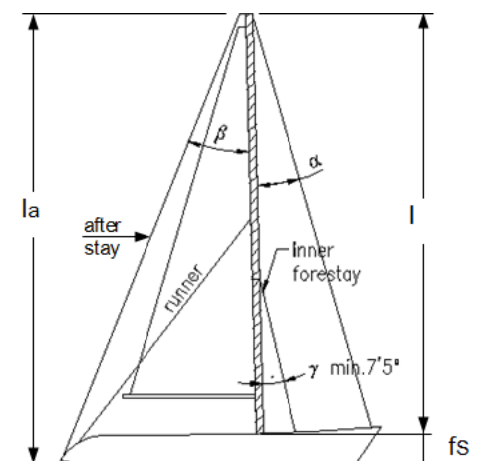


fig.17

Moment of inertia of the mast transversely (I_x)

The tension created on the shrouds and stays creates compression on the mast. The mast must have the thickness and the moment of inertia necessary to not break or buckle. The mast is divided by the various layers of spreaders into different panels and the moment of inertia of the mast section in each panel depends on the length of each of the panels and loads at the panel.

We can say that these formulas are valid for all different configurations.

The moment of inertia in the transverse direction, each panel *i* is given by the formula :

$$I_{x_i} = k_1 * m * PT_i * l_i^2 \quad [\text{mm}^4]$$

where :

k_1 = factor for each panel (see table)

m = 1 for aluminium

7.25 for wood

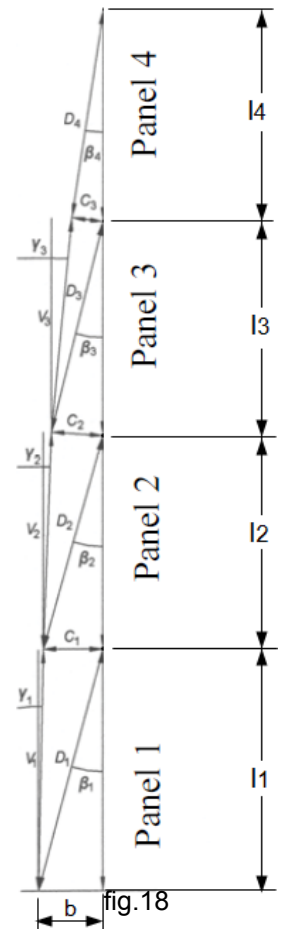
70500/E for other materials

l_i = length for each panel [mm]

Type of rig	Factor k_1	
	Panel 1	Other panels
F - 0	$2.4 k_3$	---
F - 0 short spr.	$1.6 k_3$	---
M - 1	$2.5 k_3$	3.50
F - 1	$2.4 k_3$	3.35
M - 2	$2.7 k_3$	3.80
F - 2	$2.6 k_3$	3.60
M - 3	$2.7 k_3$	3.80
F - 3	$2.6 k_3$	3.60

k_3 = 1.35 for mast stepped at deck

1.0 for mast stepped at keel



The value of PT_i to be used in each panel *i* is the maximum value of PT_{\max} deducted compression loads suffered by the lower panels. That is:

$$PT_i = PT_{\max} - \sum_{j=1}^{i-1} D_j * \cos(\beta_j)$$

where :

$$PT_{\max} = 1.5 * RM/b \quad [\text{N}]$$

b = see fig.18

Moment of inertia of the mast in the longitudinal direction (I_y)

Formula and the table of factors necessary to determine this moment of inertia.

$$I_y = k_2 * k_3 * m * PT * h^2 \quad [\text{mm}^4]$$

where :

$$PT = 1.5 * R_M / b \quad [\text{N}]$$

b = see fig.18

K₂ = stays factor (see tablea)

m = 1 for aluminium
7.25 for wood
70500/E for other materials

k₃ = 1.35 for a deck stepped mast
1.0 For a keel stepped mast

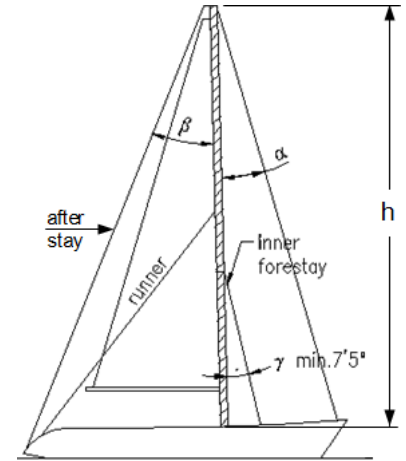


fig.19

h = height above the deck or superstructure of the highest forestay [mm]

Type of stays (see fig.16)	Factor k ₂						
	F - 0	M - 1	F - 1	M - 2	F - 2	M - 3	F - 3
1.- Double lowers	---	0.85	0.80	0.90	0.85	0.90	0.85
2.- Single lowers	---	0.80	0.75	0.85	0.80	0.85	0.80
3.- Runners & I.f	---	---	0.85	0.85	0.80	0.85	0.80
4.- Runners & c.s	---	1.00	0.95	0.95	0.90	0.95	0.90
5.- Swept spreaders	---	---	1.00	---	0.95	---	0.95
6a.- Short spreaders	1.05	---	---	---	---	---	---
6b.- No spreaders	2.00	---	---	---	---	---	---

Fractional mast top [Ref.2]

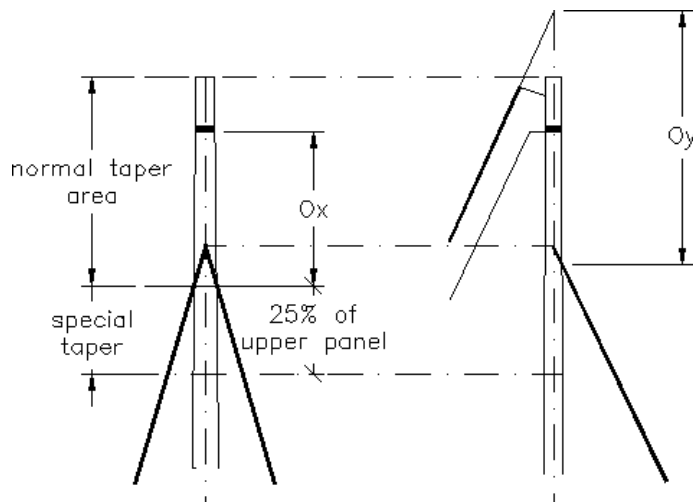
Since there is no force from a foresail on the mast, we are allowed to decrease the section modulus of the mast.

The Section Modulus for the mast top, in fractional rigs, shall at the intersection of the forestay or upper shrouds and mast be :

$$SM_x = B * RM * O_x / P \quad [mm^3]$$

$$SM_y = 2100 * RM * O_y / [\sigma_{0.2} * (O_y + h)] \quad [mm^3]$$

$$\sigma_{0.2} = \text{yield strength of mast} \quad [N/mm^2]$$



At the top of the mast the required Section Modulus is half of the above calculated.

Tapering of SM_x and SM_y might be done down to a level of 25% of the panel length below the upper shrouds/mast intersection and upper spreaders.

If O_x is less than 6% of the mast length (h), see fig.19, then the rig is considered to be a masthead rig.

MAST BASE PILLAR

The masts anchored to the deck need a strut that supports the deck and transfer mast compressive stresses to the base of the hull. We assume that this element is constituted by a steel circular, thin-walled, tube. To calculate we'll follow the procedure :

1. Consider a critical load that is equal to the compression load P_T exerted by the mast on the deck multiplied by a safety factor. The program takes this factor = 2.5

$$P_T = 1.5 * RM / B$$

$$P_{CR} = 2.5 * P_T$$

2. With a permissible tension σ_{adm} of 1700 kg / cm² calculate a reference area for the section of the pillar.

$$A_{ref} = P_{CR} / \sigma_{adm}$$

$$A_{ref} = P_{CR} / 1700$$

3. Through a catalog of tubes we choosing tubes with section areas similar to A_{ref} and using the inertia radius, we calculate for each one :

- Coefficient $C = (L/Rg) * \text{SQR} (\sigma_{adm}/E)$
- Value for the relation σ_{adm}/σ_E , which can be obtained by :

for $C \leq 1.4$

$$\sigma_{adm}/\sigma_E = 1$$

for $1.4 < C \leq 4.8$

$$\sigma_{adm}/\sigma_E = 1.235 - 0.168 * C$$

for $C > 4.8$

$$\sigma_{adm}/\sigma_E = 9.87/C^2$$

- This value is used to calculate the σ_{adm} value of the maximum permissible stress for each tube.
- Total permissible load on the tube : $P_p = \sigma_{adm} * \text{sectional Area of the tube}$
- The program provides a list of the types of tubes whose maximum load does not differ by $\pm 15\%$ of the critical load adopted P_{CR} and shows the weight of each of the options for the user to decide which he prefers to use on his mast.

SYMBOLS used

P_T load exerted by the mast on the deck [kg]

P_{CR} adopted critical load [kg]

RM righting moment that was used in the calculations of the rigging [kg * m]

B hull half-breadth [m]

A_{ref} reference area to look for tubes in the catalog [cm²]

Rg turning radius of the tube section under study [cm]

E Young's modulus of steel = 2100000 kg / cm²

σ_E yield point for steel = 2400 kg / cm²

P_p total allowable load on the pillar [kg]

Design of the boom

The boom is subject to bending forces arising from wind pressure on main sail. These forces are offset by the mainsheet (cape that allows us to vary the position of the boom to vary the angle of attack of the main) and the counter (element, which can be a mechanical part or place geared down with pulleys, which prevents the boom is lifted by effect of the tension in the sails). All this causes a horizontal force F_h and other F_v vertical in the pintle (mechanism that joins the boom to the mast).

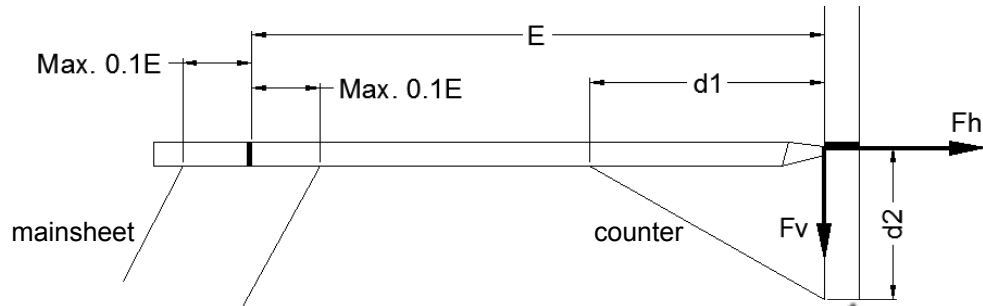
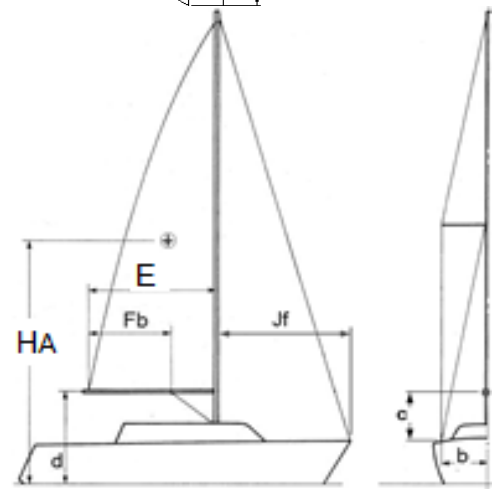


fig.20

$$F_v = 0.5 R M E / (H_A \cdot d_1) \quad [N]$$

$$F_h = 0.5 R M E / (H_A \cdot d_2) \quad [N]$$

H_A = distance from the waterline to the center of efforts of sails.



The area where the mast joins the pintle is a particularly critical area, since in this area several forces are concentrated. On one hand, the pintle is placed in the first panel, one in which the mast undergoes greater compression. On the other hand, the mast section must be able to withstand both compression and forces transmitted by the boom. As already mentioned, the boom must support certain bending forces. These forces act both vertically and horizontally, but it is noteworthy that the most important will be vertical. Therefore sections booms have different moments of inertia in the two principal directions of the section.

The NBS proposes the following calculation to obtain the boom vertical section modulus:

$$MR = (600 \cdot R M \cdot (E - d_1)) / (\sigma_{0.2} \cdot H_A) \quad [mm^3]$$

wheree :

$\sigma_{0.2}$ = yield point of the material of the boom $[N/mm^2]$

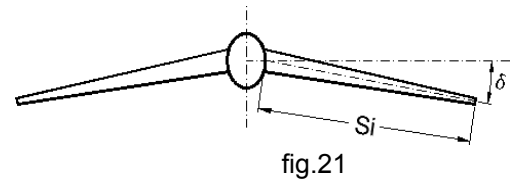
(minimum $210 N/mm^2$ for aluminium)

H_A = distance from the waterline to the sails center of efforts

E y d_1 : see fig.20

The horizontal section modulus should not be less than 40 or 50% of the vertical. The truth is that on this point there is no agreement among designers. There are technical articles betting for value and items that do on the other. On the security side you can choose to use the 50% reference value. It added that the calculation of the dimensions of the boom is only valid when the anchor point of the main sail on the boom is less than 10% at the end of the boom.

Spreaders



1. The moment of inertia of the cross section at mid-length to be :

$$I = 0.8 * C_i * S_i^2 / (E * \cos \delta) \quad [\text{mm}^4]$$

where :

E = modulus of elasticity of the material of the spreader

C_i = transverse component of the force on the shroud (see above figures)

S_i = length of the spreader

δ = angle in the horizontal plane of the spreader

2. Close to the mast the section of the spreader should have a modulus of :

$$SM = k * S_i * V_i * \cos \delta \quad (\text{mm}^3)$$

where :

$$k = 0.16 / \sigma_{0.2}$$

$V_i = V_1$ for lower spreaders

D_3 for the upper spreader

$\sigma_{0.2}$ = yield point for the material of the spreader $[\text{N/mm}^2]$
(minimum 210 N/mm^2 for aluminium)

3. Recess of the spreader must be capable of withstanding a moment of :

$$MfS = 0.16 * S_i * V_i * \cos \delta \quad [\text{N.mm}]$$

FREE-STANDING MAST

The mast is supported only on the deck and base of the ship.

We use two methods of calculation :

1. Similar to that used by NBS. I.e determine the heeling arm to 30 degrees of heel or 30 times the GZ1°
2. There follow the ISO 12217-2 standard, whereby the heeling moment due to the wind is calculated by :

$$M_W = 0.75 * V_W^2 * A'_S * (h_{CE} + h_{LP}) * (\cos\phi)^{1.3} \quad [N \cdot m]$$

where V_W is the wind speed m/s

and wind velocity needed to achieve a heeling of ϕ_T degrees is :

$$V_W = \text{SQR} \left[\frac{13 * h * T + 390 * B_H}{A'_S (h_{CE} + h_{LP}) * \cos(\phi_T)^{1.3}} \right] \quad [m/s]$$

B_H = hull breadth

To calculate M_W we'll forget this formula and take $V_W = 28$ m/s

The procedure will therefore :

- Calculate MW heeling moment necessary to heel the ship 30 degrees, according to the above formula.
- Calculate the righting moment to 30°, according to the GZ curve.
- Calculate the righting moment derived from the GZ1°. ($\Delta * 30 * GZ1^\circ$)
- Use the largest of these values to calculate the T force acting on the sail, which will decompose (see fig. 25) in a force at the top ($F_{tm} = 0.33 * T$) and the other on the 'pintle ($F_p = 0.67 * T$)

The flexural strength of the mast is given by the formula :

$$E \cdot I = \frac{k^2 \cdot P_{cr} \cdot L^2}{\pi^2}$$

Where k is a constant depending on the type of fastening of the mast at their ends.

In this case the mast simply pads to the base and the cover (c.4 and c.5).

To equal the other parameters, the worst case of potential is the one with the highest value of k , corresponding to the mast fixed on the base by a hinge. I.e, the base can not move but can rotate.

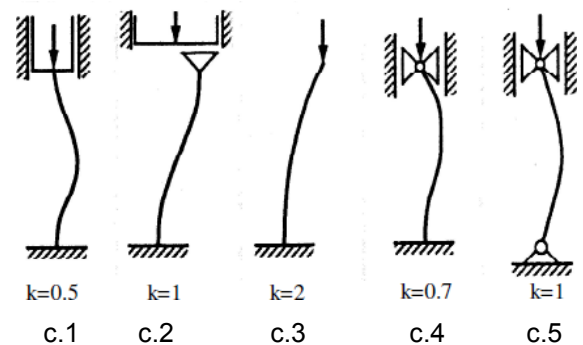


fig.24

This is the model (c.5) we use to calculate the forces on the mast and the reactions on its supports.



The first simplification adopted will be to assume that the force exerted by the sail on the mast has a triangular distribution ranging from a zero value at the top of the mast, to a maximum value in the rachis, which currently do not know.

As does the NBS, it is assumed that the total force on the sail makes the boat heeling 30°. That is, the resulting force **F** acting on the sail, which is located on the CE sail exerts a heeling moment equal to the righting moment of the hull at 30°: **RM₃₀**. (here could be added the crew doing counterweight in the band)

The boat rotates around the axis of the water plane, so can be write

$$F * h = RME_{30}$$

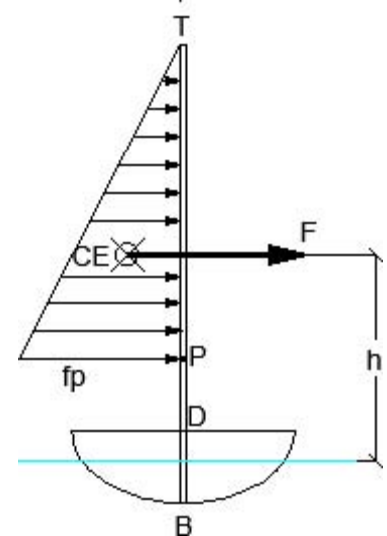
This allows us to deduce the value of **F** :

$$F = RME_{30}/h$$

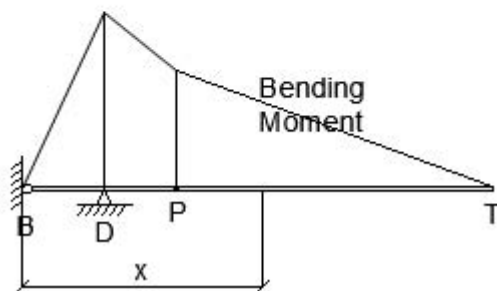
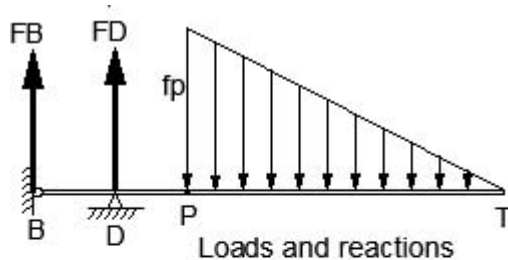
This is the resultant force of the triangular load, so :

$$F = f_p * PT / 2$$

$$f_p = 2 * RM_{30}/(h * PT)$$



This is the model for the beam / mast we'll study :



And the equilibrium equations :

$$BM_P = F * PT/3$$

$$BM_D = F * (DP + PT/3)$$

$$FD = BM_D/BD$$

$$FB = F - FD$$

Bending Moment values along the mast :

$x > BP$:

$$BM_x = f_p * (x - BP) * (BT - x)^2 / (6 * PT)$$

$BD \leq x \leq BP$:

$$BM_x = F * (x - BD + PT/3)$$

$x < BD$:

$$BM_x = x * BM_D/BD$$

ISO 12215-5 gives values for design stresses (σ_d) for various materials: glass fiber, carbon, aramid (Tables C-4 to C-7), woods (Table E-1), aluminum (Table F-2)

The permissible stress σ_{adm} for mast material, adopting a safety factor of 3, is equal to:

$$\sigma_{adm} = \frac{\sigma_d}{3}$$

Tabla F.2 – Propiedades mecánicas y tensiones en compresión para los refuerzos metálicos

Valores en newtons por milímetro cuadrado

Tensiones de diseño para los refuerzos											
Acero dulce				σ_u	σ_{uw}	σ_y	σ_{yw}	σ_d/σ_y	σ_d	τ_d	
E24 / A				400	400	235	235	0,8	188	106	
E32 – AH 32				470	470	315	315	0,8	252	142	
E36 – AH 36				490	490	355	355	0,8	284	160	
Aleaciones de aluminio (sin tratamiento térmico)											
Referencia EN	Producto y espesor	Composición	Estado	σ_u^a	σ_{uw}^a	σ_y	σ_{yw}	σ_d/σ_y	σ_d^b	τ_d	
EN AW-5052	Plancha, banda, chapa 3 < t < 50	Al,Mg 2,5	H32	210	170	160	65	0,7	46	64	
EN AW-5052	Plancha, banda, chapa 3 < t < 50	Al,Mg 2,5	H34	235	170	180	65	0,7	46	72	
EN AW-5754	Plancha, banda, chapa 3 < t < 50	Al,Mg 3	0/H111	225	190	80	80	0,7	56	32	
EN AW-5754	Plancha, banda, chapa 3 < t < 50	Al,Mg 3	H24	240	190	190	80	0,7	56	76	
EN AW-5154A	Plancha, banda, chapa 3 < t < 50	Al,Mg 3,5	0/H111	215	215	85	85	0,7	60	34	
EN AW-5154A	Plancha, banda, chapa 3 < t < 50	Al,Mg 3,5	H24	240	215	200	85	0,7	60	80	
EN AW-5086	Plancha, banda, chapa 3 < t < 50	Al,Mg 4	0/H111	240	240	100	100	0,7	70	40	
EN AW-5086	Plancha, banda, chapa 3 < t < 50	Al,Mg 4	H34	275	240	185	100	0,7	70	74	
EN AW-5083	Plancha, banda, chapa t < 6	Al,Mg 4,5 Mn 0,7	0/H111	275	275	125	125	0,7	88	50	
EN AW-5083	Plancha, banda, chapa 3 < t < 50	Al,Mg 4,5 Mn 0,7	H32	305	275	215	125	0,7	88	86	
AA 5059 Alustar	Plancha, banda, chapa 3 < t < 50	Al,Mg 5-6	0/H111	330	300	160	160	0,7	112	64	
AA 5059 Alustar	Plancha, banda, chapa 3 < t < 50	Al,Mg 5-6	H32	370	300	270	160	0,7	112	108	
EN AW-5383	Plancha, banda, chapa 3 < t < 50	Al,Mg 4,5 Mn 0,9	0/H111	290	290	145	145	0,7	102	58	
EN AW-5383	Plancha, banda, chapa 3 < t < 50	Al,Mg 4,5 Mn 0,9	H32	305	290	220	145	0,7	102	88	

We'll take as design stresses :

- Aluminium 210 N/mm²
 - Wood 70 N/mm²
 - Glass fiber 150 * Ψ + 72 N/mm²
 - Carbon fiber 610 * Ψ – 55 N/mm²
 - Aramide 250 * Ψ N/mm²
- } Ψ It is the % in weight of fiber content (global value)

but the user can set the value he considers most appropriate for study.

BOOKS AND ARTICLES VIEWED

1. Nordic Boat Standards
2. Principles of Yacht Design by Larsson Eliasson
3. "Design and Engineering aspects of Free-Standing Masts and Wingmasts" by Eric W. Sponberg
4. "Diseño de la jarcia, arboladura y apéndices de veleros", Willian Pelgram para el Curso Avanzado Diseño y Tecnología de Yates (Fundación Ingeniero Jorge Juan)
5. "Best Mast: a new way to design a rig" by Robert Janssen Msc, Centre of Lightweight Structures TUD-TNO, Netherlands
6. "Elements of Yacht Design" by Norman L. Skene
7. "Sail boat Mast Design " by Alexandre Bergeron, thesis supervisor : Dr. Natalie Baddour, Department of Mechanical Engineering, University of Ottawa
8. ISO 12215