The Design of Sailing Yachts - Vol 2

Pierre Gutelle

Translation of Chapter VI (pages 243 to 293) via Anthony Pearce

VI MASTS, RIGGING AND SAILS

Perhaps the steps followed in this chapter may seem illogical, since it consists in studying the mast and rigging before looking at the sail plan.
It will be seen that it is of no consequence since it will make it possible to better understand the restrictions imposed by the mechanics of rigging on the definition of the sail plan. Before knowing what to draw it should be known why one draws it and to be aware of the constraints which there are.

Of all the elements constituting the yacht, the mast and rigging is certainly that which is the cause of the greatest number of accidents, especially in races where one always seeks to reduce the weight to the minimum, not only to improve stability but especially to decrease the moment of inertia, which has an extremely negative factor on the movement of the boat.

There exist many methods of calculation, more or less simplified, sampling of the masts and their rigging as of the calculations established by manufacturers of masts, however these give only relatively vague results because of the ignorance of two essential fundamental elements required to carry out these calculations: the mechanics of the sail-mast-rigging unit and the value of the static and dynamic loads.
With the second question, it will be possible to give an answer based on a series of in-situ measurements in all kinds of conditions and for sizes and types of yachts and riggings as different as possible.
Currently very few studies of this kind were concluded, the Majority within the framework of the America's Cup, thus for only one type of yacht, the 12 m J.I., and less still were published.
Very recently the INERN has just finished a very interesting study campaign on two identical quater tonners. It remains to analyse and extrapolate these results.
In addition such studies do not have a value of practical range unless they are analysed and defined according to a correct knowledge of the mechanics of the system and it is thus there that we will start.

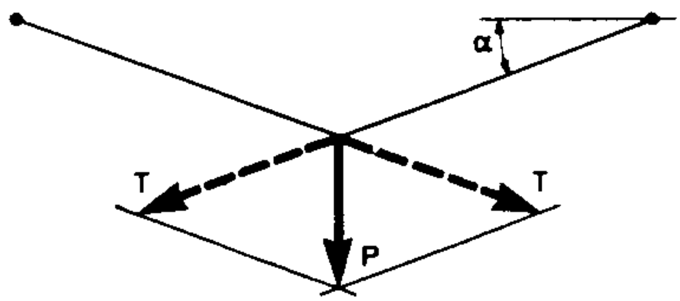
VI-I - THE MECHANICS OF THE RIGGING

The comprehension of the mechanics of a rig results from of the knowledge of a number of disparate elements.
We will thus start by analysing these to constitute a kind of puzzle from where a complete theory will emerge.

VI-I - 1. - BEHAVIOR OF A CABLE SUBJECTED TO A TRANSVERSE LOAD

One considers a horizontal cable attached between two points and supporting a load P (fig. VI-1) which will induce a tension T in the cable related to the angle between the two adjacent parts of the cable*. If α is the angle which forms the cable to the horizontal: T = P / (2 sin α).

Fig. VI-I. Tension in a cable supporting a localised load is a function of the angle that it makes with the horizontal and vice versa.



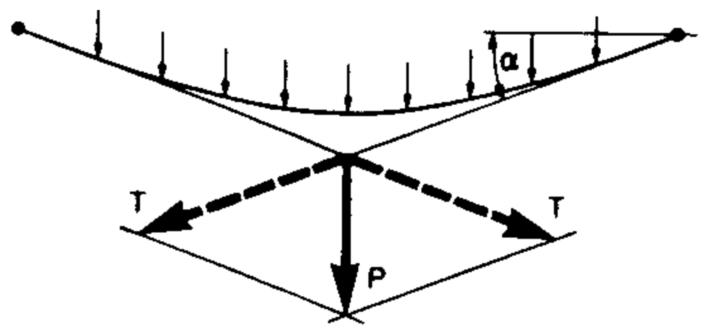
One immediately sees that for a given load, as angle α is reduced the tension T will increase; tending towards ∞ when α tends towards 0 (table VI-I).

TABLEAU VI-I

α°	1/(2 sin α)
30	1
15	1,93
10	2,88
5	5,74
2	14,33
1	28,65

Consider now, instead of a concentrated loading, we apply a uniformly distributed load over a certain length of the cable; these will make at the corresponding distance a curve in the shape of a chain (fig. VI-2).

Fig. VI-2. When the cable supports a load uniformly distributed on a part its length, the angle that it makes at its ends is the same one as if an equal load was applied locally.



In this case the extensions of the cable beyond the part carrying the load are tangent at its ends and the tension is always: T = P / (2 sin α), P being then the total of the distributed load on the cable. The maximum force: $f_m = 0{,}25 \cdot l \cdot \tan \alpha$.

It would be the same if the load was not uniformly distributed, but then the shape of the curve would be different just as its maximum force.
Third case, we add to the cable subjected to the uniformly distributed load a concentrated loading (fig. VI-3). At the two points considered the prolongations of the cable will not be tangent any more with the curve but will be directed according to the resultant of the tension in the cable and the concentrated loading.

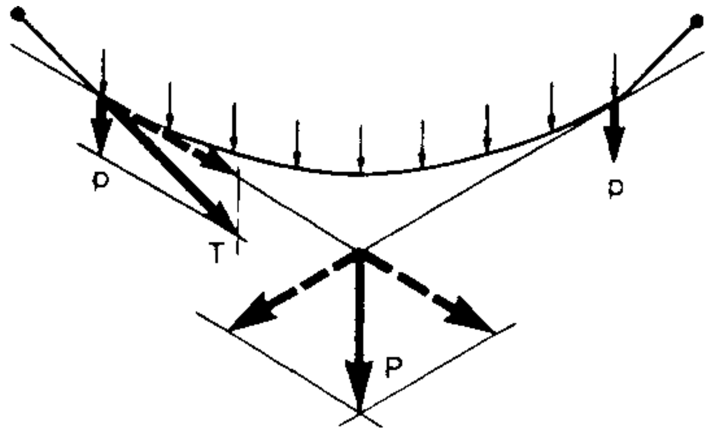


Fig. VI-3. *A local load applied at the end of the part supporting the distributed load modifies the direction of the tension of the cable according to the resultant of the local load and the initial tension due to the distributed load.*

STIFF STAY, SOFT STAY

Many controversies develop around the problem of the stiffness of the forestay for yachts owing to the fact that the ideas on this question are not always very clear.
What we have just exposed must make it possible to better understand the elements, which should be taken account of.
If we consider a unit whose rigidity ensures a quasi-stability of the distance between the points of attachment of the cable, the direction that these will take will be related to its elasticity; the greater the elasticity the greater the deflection, but with less elasticity the tension in the cable will be high (because of the augmentation in the angle α) (fig. A).

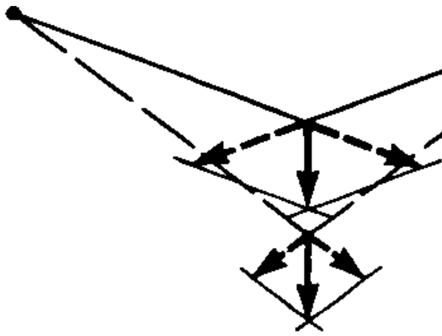


Fig. A

If we consider now that the distance between the points is not fixed any more but that it is the tension that is constant, the deflection ratio will remain constant like the angle α (fig. B).

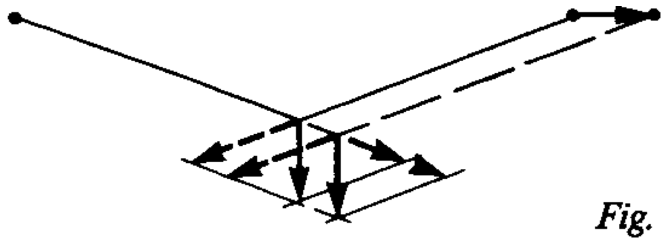


Fig. B

It manifests that the forestay of a yacht enters the second case since the mast shell cannot be regarded as rigid and that the behaviour of the forestay is balanced only by the tension of the cap-shroud, of the backstay and the load of the mainsail. If the tension of the first cannot be defined that a priori the two others have all kinds of mechanisms (hoists, turnbuckles at wheel, hydraulic actuating cylinder) to balance the load of the forestay during sailing.
As the speed increases, the force of the wind increases, and load in the forestay will increase, the load of the mainsail will also grow and it will be enough to increase the tension of the backstay to maintain constant the deflection ratio in the forestay.

The longitudinal displacement of the head will be made in a regular way backwards. The use of a rod in the place of a cable would make it possible to reduce this displacement, which, by increasing the rake, tends to make the yacht more fiery, which it already has a tendency to become when the wind increases. Nevertheless, taking into account strong longitudinal accelerations to which the rigging is subjected, it is necessary to preserve a certain elasticity at the forestay and I share on this point the opinion of Rod Stephens who recommends the use of the rod for this.

This elasticity has besides for other favours, by deadening the movements of the jib, to maintain a certain stability of the streamline flows on the sail.

EFFECTS OF THE PRETENSION OF THE SHROUDS

It is interesting to see on this occasion how the masthead unit will behave.
With the yacht in dock, an important pretension is applied to the cap-shrouds, which will result in compression of the mast (fig. C-a).
When the yacht is under way, the side component of the masthead unit transfers a part of the tension from the leeward shroud to the windward shroud, nevertheless the resultant of compression in the mast remains constant (fig. C-b). This until the totality of the tension in one is passed to the other.
During the first two phases, compression in the mast (at least for the share due to the cap-shrouds) remaining constant, this generates additional shortening of the mast and leeward displacement of the head will be dependant only on the lengthening of the shroud.
Beyond this, the tension of the shrouds will continue to grow but also the compression in the mast (fig. C-c). This will be shortened from where a leeward displacement of the head is increasingly important.
It is thus necessary for the stability of the adjustments of the mast that the shrouds are the least elastic as possible, where for interest for the latter of the round or shaped bar whose lengthening is around 1/1,5 of that of a cable [1 x 19].

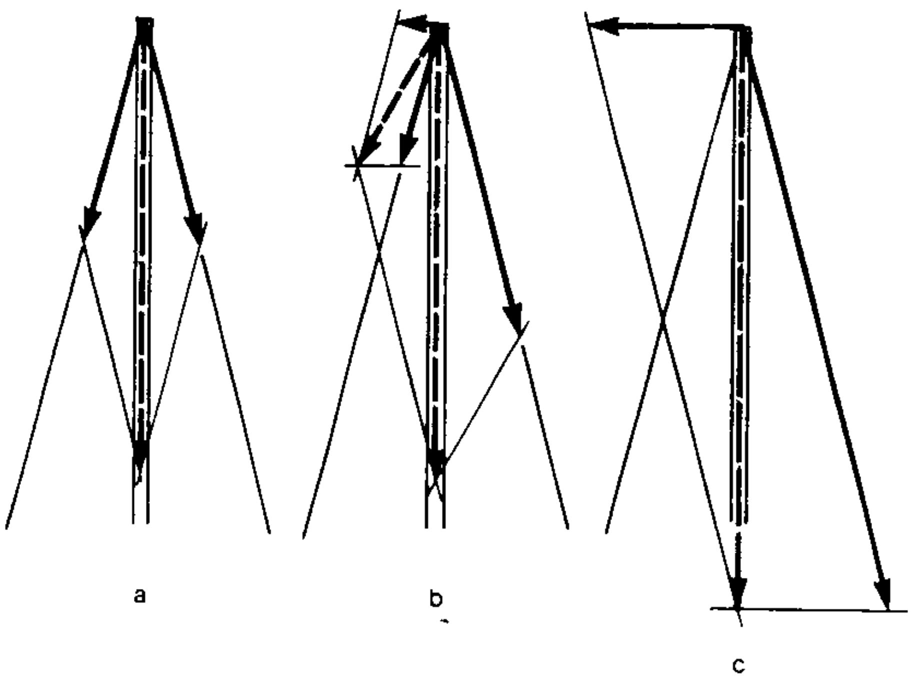
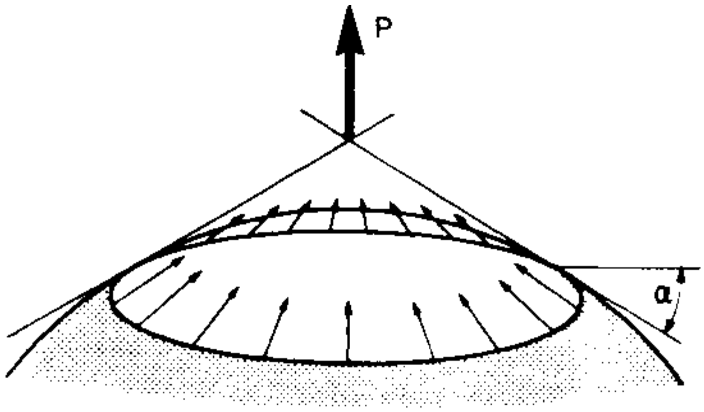


Fig. C

VI-I - 2. - DISTRIBUTION OF THE LOADS IN THE FABRIC OF A SAIL

We know that each element of the surface of a sail is subjected to a load due to the difference in pressure between the airflow on its two faces.
If the sail were a sphere, this effort would be uniformly distributed all around the elements of a segment of a corresponding sphere, according to a cone having for axis the direction of the effort and whose surface is tangent to the sphere in extreme cases of the surface considered (fig. VI-4).
Seen in plane the distribution of this load would radiate uniformly around its point of application.
The problem is the same as the preceding one, though instead of applying to a simple line it now interests a circular surface.

Fig. VI-4. *The resultant of a pressure P exerted on a segment of a sphere is a load uniformly distributed on the circumference of this one*



The tension per unit of length on the circumference of surface considered is then
$T = P \sqrt{(4\pi S)} / (4 \sin \alpha)$, $\sqrt{(4\pi S)}$ being the length of the circumference of surface S and α the angle of the generator of the cone with the surface.
In fact, for multiple reasons related to the shape of the sail (different camber in the transverse and vertical direction), stiffness of fabric, tension in the foot, the distribution of the effort in the fabric according to a very flattened ellipse and the tension tends towards a value $T = P / (2 \sin \alpha)$ by unit of width.

VI-I - 3. - DECOMPOSITION OF THE LOADS IN A JIB

The resultant of the aerodynamic loads acting on a jib is a force appreciably perpendicular to the plane surface supported at the three points of the head, the tack and the clew. If the pressures were distributed uniformly on the sail this resultant would pass through the centre of area of the triangle defined by the three points of attachment. At the interior of the surface of the sail the tensions are distributed as we saw previously, resulting, in each side of the triangle, in longitudinal and normal forces inside the three triangles having for top the centre of area of the foot, the luff and the leach (fig. VI-5).

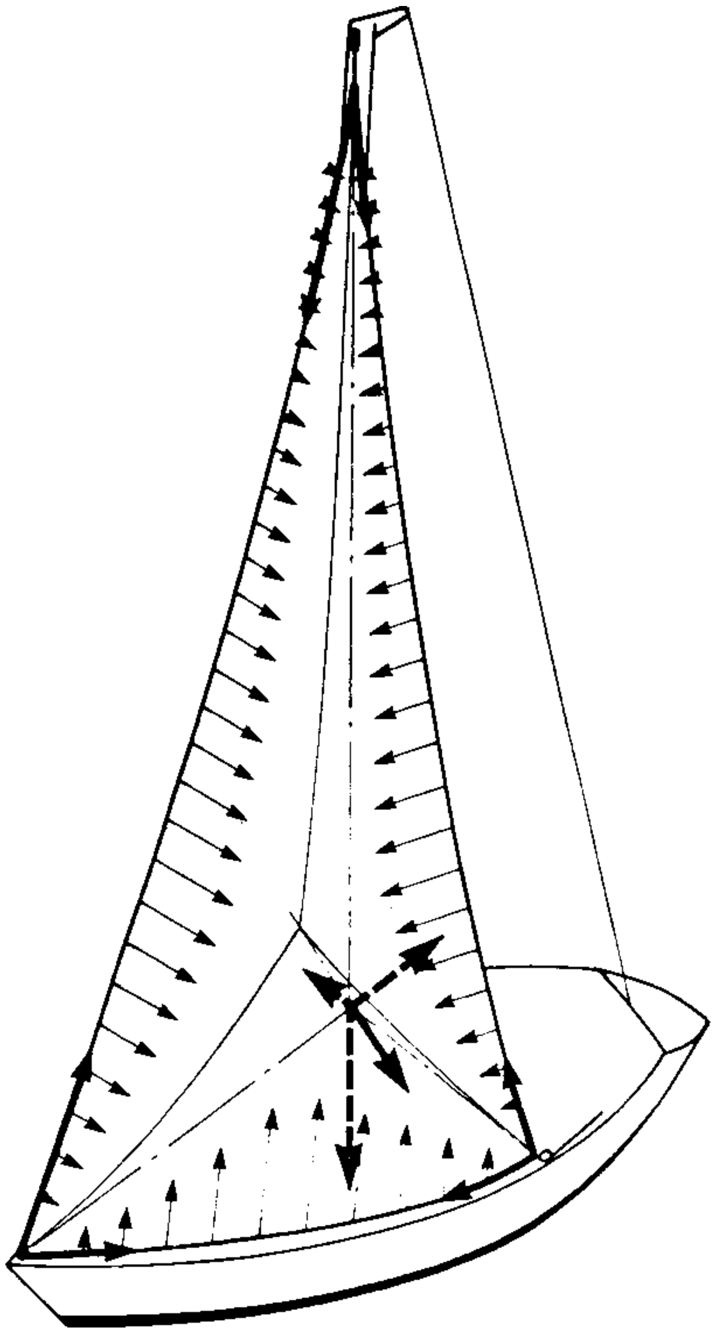


Fig. VI-5. The Aerodynamic Force developed by a jib breaks up into three tangent forces at the three points of the sail and whose direction is determined by the halyard, the clew and the tack. The tensions developed in the fabric break up into loads normal and parallel to the three sides of the sail.

Along each side a longitudinal tension and a normal effort distributed over the entire length will thus develop, both of aerodynamic origin. This last acting on the edge as in the figure V-2 will induce another longitudinal tension, of mechanical origin this time, being added to the preceding one.
The whole results in three forces applied at the three points of the sail, convergent, tangent with the sail and whose resultant is the aerodynamic load.

In reality, the non-uniform distribution of the pressures, the form given by the yacht to the sail and the modification of the tension in the foot (intended to preserve or modify the shape) make that the aerodynamic resultant does not correspond to the centre of area of the sail. Its position is generated by the decomposition of the three points of the sail by the direction of the stay (or the halyard), of the pendant of the tack (when there is one) and of the clew, and that all these directions are tangent with the sail at these points.

VI-1 - 4. - DECOMPOSITION OF THE EFFORTS IN A MAINSAIL

If the mainsail were fixed only in its three points (as this is the case for the mainsails on a roller) the problem would be the same one as for a jib. The reason of the difference holds in the fact that two of the three sides, the foot and the luff, are integrated on the mast and the boom.
The stresses in the fabric normal to these boltropes are thus boxed by these spars without it being necessary to balance them by a longitudinal tension. We are not any more in the case of the cable of paragraphs 1 and 2 above, this being replaced by a rigid element ensuring by its stiffness its own flexural strength.

The longitudinal forces in these boltropes are thus much weaker and their tension, in more of the balance of the longitudinal aerodynamic components, is intended to cause the deformation of fabric to maintain the shape of the sail.

The situation is quite different for the leach whose normal efforts must be balanced by a longitudinal tension, as with the jib. It is primarily this tension that will be taken by the halyard and the clew.
The normal efforts which will be exerted on the spars will thus have these quite distinct origins:
- on the one hand those due to the adjacent part of the sail which will be distributed appreciably according to a triangle whose top is with height of the centre of aerodynamic pressure (fig. VI-6a);
- in addition those due to the tension of the leach which are decreasing from the points of halyard and clew towards the point of tack (fig. VI-6b). Both being added by giving a distribution in the shape of an amphora (fig. VI-6c).
In each point of the luff, the corresponding force is of course tangent with the sail and the angle of the sail will determine the longitudinal and side components acting on the mast and the boom.

As soon as one wants to calculate with precision the section of a mast it is impossible to be unaware of the induced bending stresses. One unfortunately does not have any precise information on their value, their direction and their vertical distribution, not only according to the speed and forces of the wind but also according to the configuration of reefing of the sail, which causes a displacement of their distribution. It is one of the most ignored causes of failure of the mast, in particular for the flexible masts which can work in buckling like a simple column but with compression and inflection combined, the latter being balanced only thanks to the presence of the sail and possibly the running backstay.

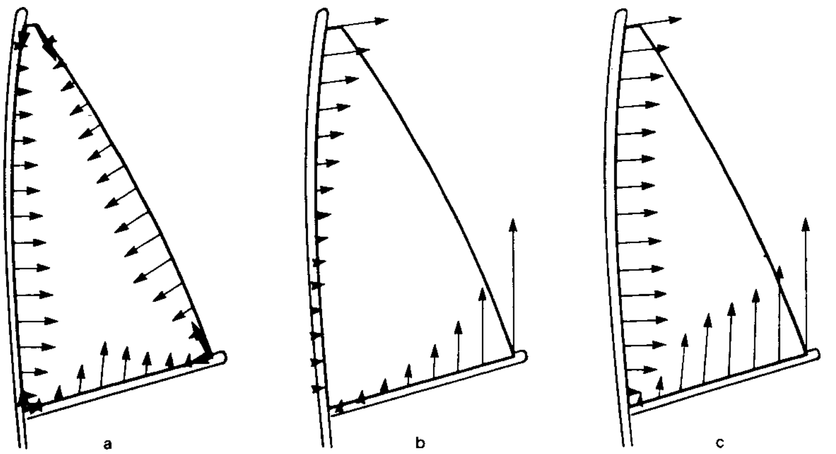


Fig. VI-6. In a mainsail the tensions in the fabric break up into loads normal and parallel at the three sides (a). But whereas on the foot and the luff the normal efforts are taken up by the spars, on the leach one needs to exert a strong tension to balance them. These tensions break up on the one hand into compressive forces in the spars and, on the other hand, into normal efforts decreasing from the points of halyard and clew towards the point of tack (b). The sum of all these normal efforts is composed according to a form close to that represented in (c), the envelope of these forces being tangent to that of the sail along each spar.

VI-1 - 5. - VARIOUS NODES AND PANELS OF A MAST

We should now make the analysis of the loads acting on the various parts of a mast, and analyse which will be broken up, as it is usual to do, according to two planes, longitudinal and transverse. It is from this that we will be able to understand how it really works. To simplify, we will first of all consider a mast intended for rigging at the head on a yacht for close-hauled sailing (fig. VI-7) because it is the situation where the loads are highest.

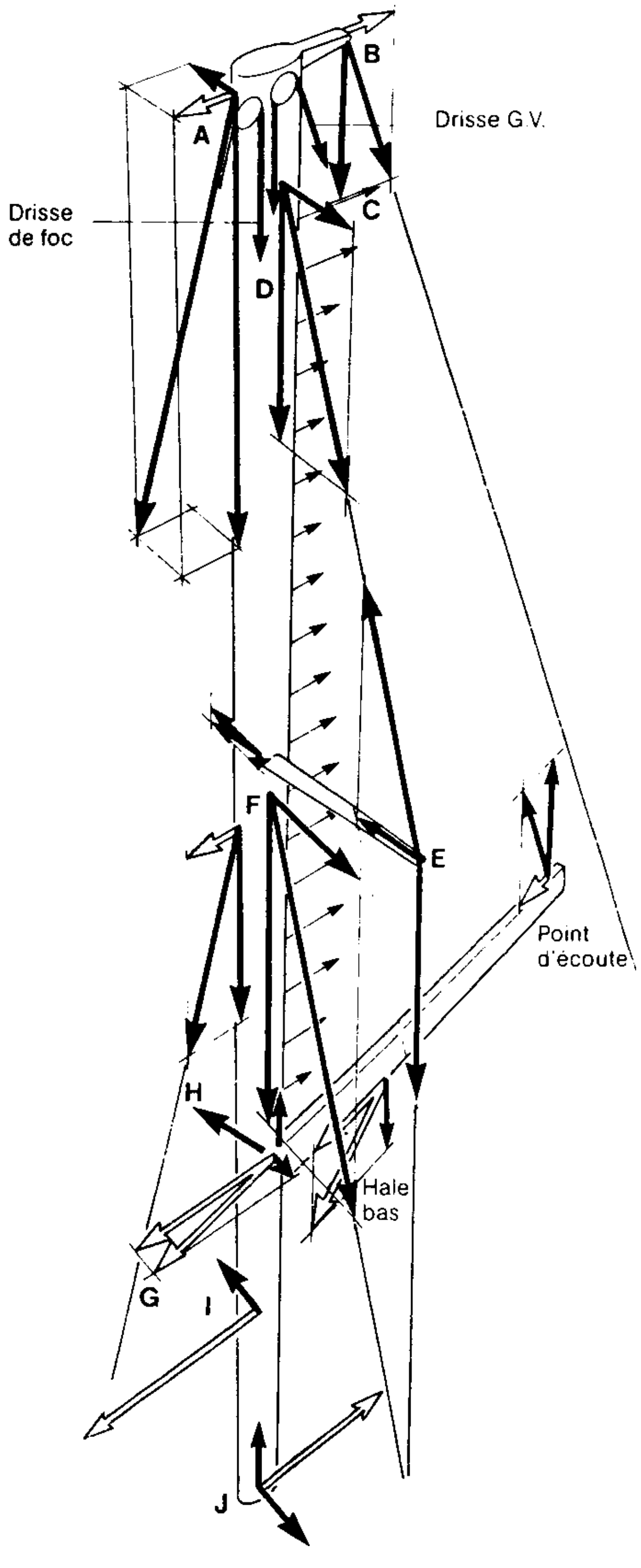


Fig. VI-7. *Various forces being exerted on the mast. The lateral components of the force exerted by the mainsail are not represented because they are hidden by the mast. The length of the arrows representing the forces does not represent any specific value but is purely indicative. The side and longitudinal forces represented at I (the deck) and at J (the foot of the mast) are the actions exerted by the mast on the hull.*

VI-I - 5.1. The head and the higher panel of the mast

One will find there:
* The forestay unit and halyard (A) whose load will be exerted downwards, before and under the wind. One will be able to break this one up into three forces: a vertical along the axis of the mast, lateral to the lee and longitudinal forwards. For the vertical force it will be necessary to add the return of the jib halyard.
It should be noted that the angle, in the longitudinal plane, between the forestay and the mast which, on a normal level of sail is around 20° is actually considerably reduced, being able to reach values lower than 10°, because of the deflection of the forestay at the head of the sail caused by the leach load. The reduction will be even more dramatic with a flexible mast because of the slope of the top backwards.
* The backstay (B) ensures, at least partially, the balance of the longitudinal load of the preceding unit. Its load breaks up into a vertical force and a longitudinal force directed aft.
When the backstay is double there is a side load with the wind but a very reduced component because of the small separation of the two cables.
An important point is to be noted here. The total resultant of longitudinal loads of the backstay and the forestay, in particular if the longitudinal angle of the backstay is small or if it is fixed at the end of a long bracket [backstay crane], is only approximately in alignment with the centre of area of the section of the mast. Their offset will induce a bending moment, which can be important for the balance of the mast, and a torque.
* The mainsail (C) exerts, on the one hand, by its halyard (of which the return should not be omitted), a vertical load including the vertical component of the load of the luff and, on the other hand, a horizontal load distributed on the height of the panel and that one will break up laterally, to the lee, and longitudinally backwards. This load will induce longitudinal and lateral bending stresses in this part of the mast.
* The cap-shroud (D) is intended to balance the lateral forces directed to the lee. Because of its angle it will induce a component of compression in the mast.

VI-I - 5.2. Intermediate Rigging

At this level one will find:
* The spreader (E) returns the cap shroud to the vertical and so is subjected to a compressive force. To avoid any other stress in the vertical plane it is fixed according to the bisection of the angle of the cap shroud, and so induces a small vertical component in the mast.
Its compressive force on the mast must be set out on the greatest possible longitudinal surface area in order to avoid any risk of deformation of the section.
* The intermediate staying, whatever its provision, has several functions (F):
- In the transverse direction it balances on the one hand the compression of the spreader and on the other hand a part of the side load of the main sail.
- In the longitudinal direction it must balance the longitudinal load of the main sail, directed aft but also limit the movements of the mast forwards or aft caused by the dynamic loads. It must also take part in the balance of the longitudinal and transverse forces of the boom. It must thus ensure an omnidirectional positioning of the mast in the horizontal plane. This implies the setting out to each side two lower shrouds, or an aft lower and a baby stay. However, under certain conditions, the function of balance of the longitudinal forces of the mainsail can only be provided by the boom or with the bending moment applied at the head of the mast by a shift of the forestay compared to the backstay or even to the mainsail.

VI-I - 5.3. The Lower Panel and Gooseneck

When the mast has several sets of spreaders, the process previously described is found at each spreader and the adjacent panels, this is why we will pass directly to the lower panel limited by the gooseneck on which the boom is articulated.
* In this panel we always find the flexural forces induced by the mainsail.
* The effort (G) that the boom exerts on the mast has two origins: on the one hand the horizontal component of the load from the leach at the clew (the equivalent of the vertical load on the halyard), on the other hand the horizontal component of the load of the vang.
If the clew of the mainsail does not lead exactly in a transverse vertical plane, a component of compression will appear (positive or negative according to the orientation) which will come to be added to that of the vang.

The orientation of the boom breaks up this compressive force into a lateral force with the wind (weak when close hauled) and a longitudinal force forwards. These will balance a part of the forces exerted by the mainsail.

The gooseneck will also have a transverse effort (H) directed to the lee and perpendicular to the boom, representing the share of the lateral forces of the sail exerted on the boom, the other share being provided by the lateral component of the load of the clew. Its value will vary according to the relative position of the point of attachment of the mainsheet and the resultant of the side forces exerted on the boom, this component tends to be cancelled when the mainsheet is about the middle of the boom.
The lateral and longitudinal components of H (not represented on the figure) will depend on the angle of the boom.

The vertical component of the vang at its fixing point will act as compression upwards directly from where it is fixed on the mast, or starting from the foot of the mast in the contrary case.
One will also find with the gooseneck a compressive force from bottom to top resulting from the balance of loads in the luff.

VI-I - 5.4. The foot of mast

One will find at the foot of the mast, the resultant of all the compressive forces as well as lateral and longitudinal forces balanced by corresponding reactions.
In the case where the mast passes through the deck (I) this will act like a support and its reaction will modify of course the distribution and (or) the direction of the horizontal forces at the foot of the mast. This is modified by the attachment of the vang.

Figure VI-8 shows a summary the whole of the forces perpendicular to the mast that will induce bending stresses. One immediately sees the importance of the positioning of the anchoring points of the stays to obtain a correct balance.
Thus, if the point of attachment of the cap shroud does not ensure balance between the load of the forestay-halyard on the one hand and the higher part of the mainsail on the other hand, the mast will be curved with the wind if the point is too low (fig. VI-9a) or into the wind if it is too high (fig. VI-9b).
In the same way, the position of the lower-shroud or the intermediate shrouds must ensure the balance of the forces of the mainsail load on both sides of its point of attachment. If it is too low, the low part will come into the wind (fig. VI-9c) and, if it is too high, with the wind (fig. VI-9d).
A mast with well-balanced rigging will see in fact all its panels to curve to the lee (fig. VI-9e).

Unfortunately this balance is very theoretical because the forces operating the mast are eminently variable according to which jib is hoisted, their shape, their adjustment, the possible reefing of the mainsail and, of course, the force of the wind, without speaking about the dynamic variations due to the movements of the yacht.
All this is of little importance as long as the mast is rigid, of strong section and can be regarded as a column. It is not the same when bending of the mast exceeds the dimensions of the section.

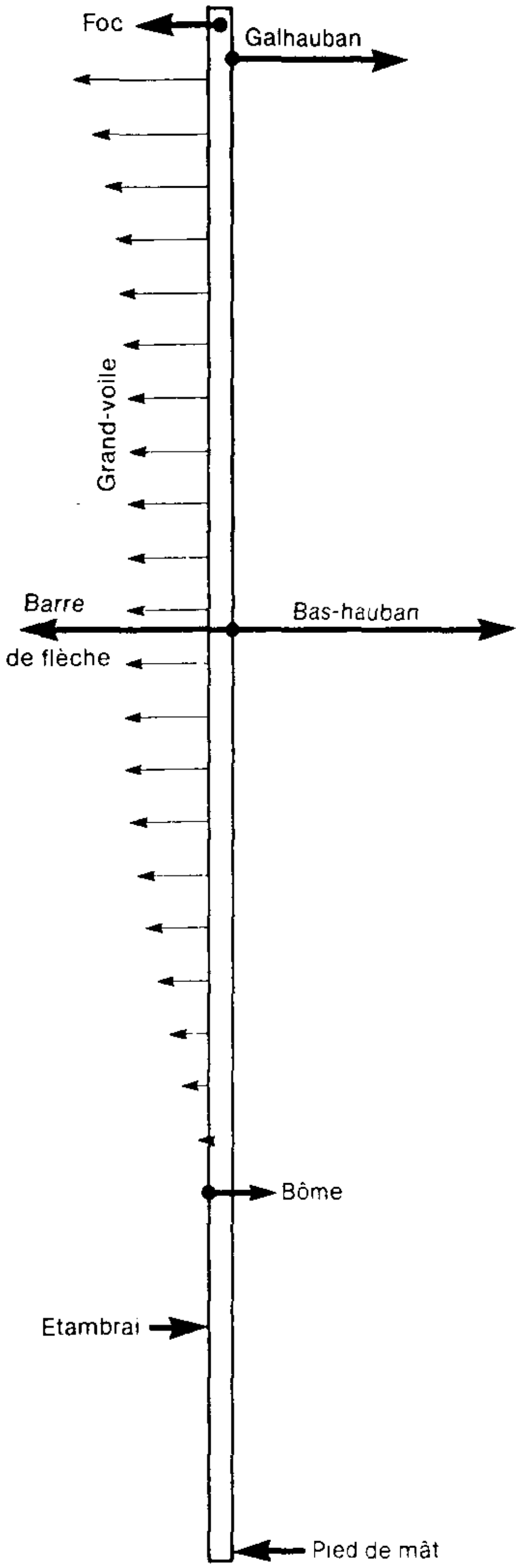


Fig. VI-8. *Summary of the different forces being exerted laterally on the mast. The force exerted by the boom maybe being positive or negative, according to the position of the point of attachment of the mainsheet.*

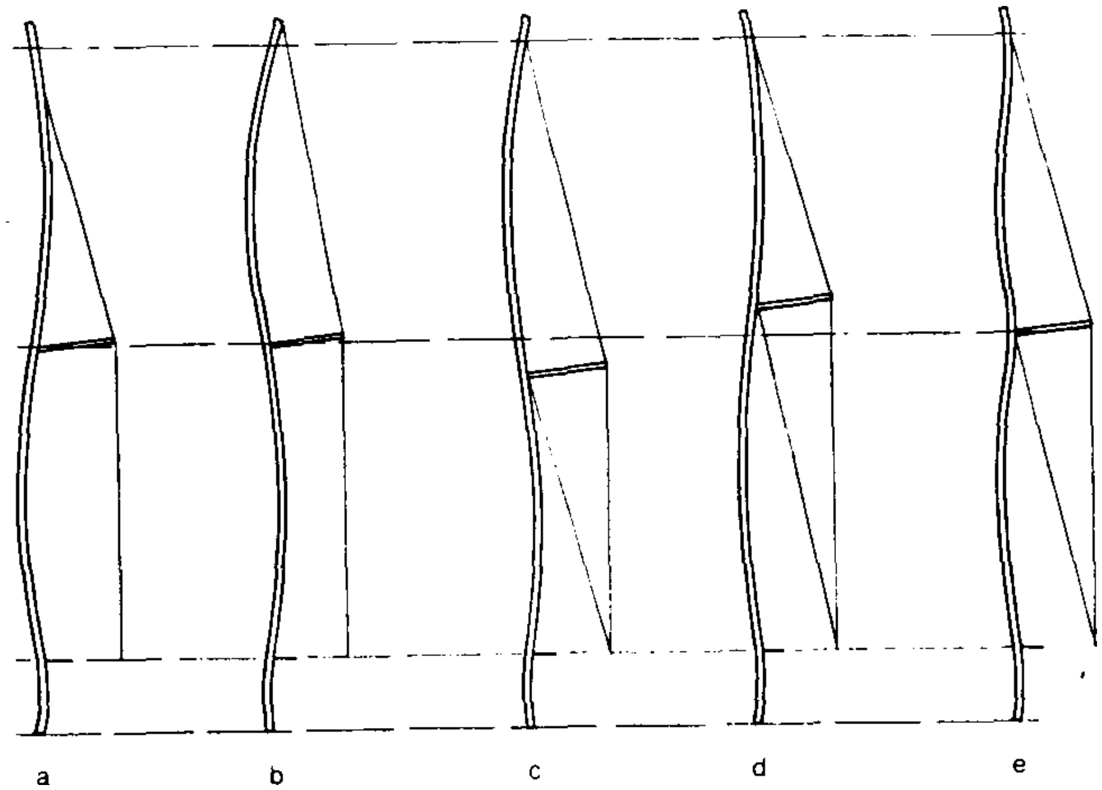


Fig. VI-9. *Deformations (exaggerated) of the mast according to the position of the attachment points of the shrouds.*
a – cap shroud too low; b – cap shroud too high; c – lower shroud too low;
d – lower shroud too high; e - correct positions;

VI-I-5.5. The case of the flexible masts

We will see that when the rigging is not at the head (3/4 or 7/8 rig for example) the preceding balances are modified.
In the simplest case of a light centreboard yacht, which in general includes only one forestay and a stay to each side, the balance of the load of the forestay-halyard is ensured by the side-shroud and the weight of the crewmember on the trapeze, which will act mainly in the transverse direction (fig. VI-10), and by the load of the mainsail for the longitudinal direction.

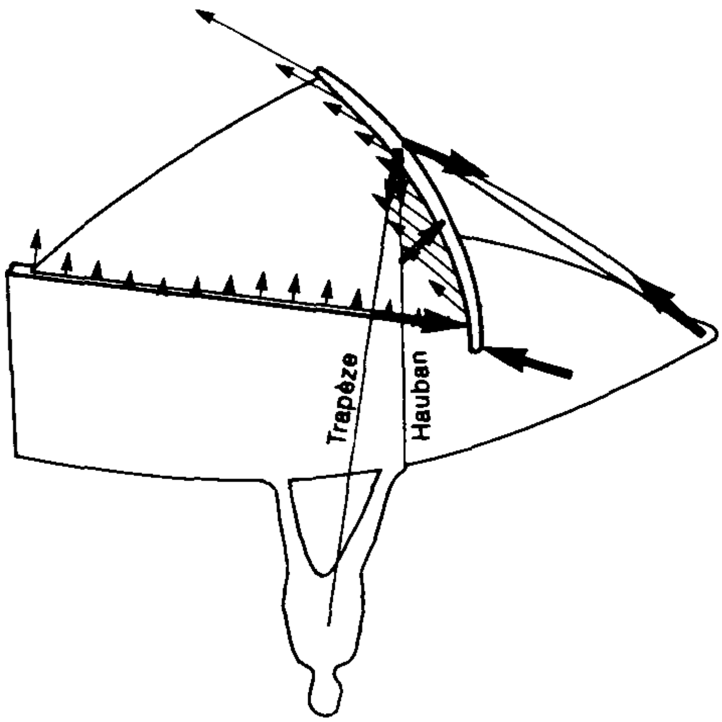


Fig. VI-10. *On a centreboard yacht, the balance of the load of the forestay is almost entirely* taken by *the load of the mainsail. The position of the rigging of the side-stay thus defines the essence of the balance of bending, this being nevertheless* controlled by *the spreader (mainly in the lateral direction) and by the pressure of the boom (mainly in the longitudinal direction).*
The side stay and the trapeze support *the balance of the side components.*

The position of the point of attachment of the forestay compared to the mainsail will thus have a very important effect on the deflection of the mast in the longitudinal direction; the lower this point the more the deflection, the pressure exerted by the boom accentuates it.
The position of the point of fastening of the side-shroud and the trapeze will be defined not only compared to the mainsail but also compared to the point of attachment of the forestay-halyard. Indeed, if this is too low (for side balance) one can correct for its effects by raising the fixings of the side-stays and the trapeze.
The pressure of the boom will have, of course, also a lateral action similar to that which it has in the longitudinal direction.
Two elements will make it possible to control bending: the staying (in the two directions) and possibly the spreader (primarily in the transverse direction).
A spreader pushing will reduce bending to the wind, whereas pulling, the spreader increases it.

It will intervene in longitudinal control insofar as, when the mast is curved forwards, the assembly of the two spreaders is rather rigid so that, the unit swivels around the windward shroud (fig. VI-11), the end of the leeward spreader comes to take support on its shroud. The adjustment of angle A between the spreaders at the time of this action constitutes an additional method of control of longitudinal bending. It however requires a very solid fixing of the spreader on the mast because of the lever-arm that this exerted force represents.

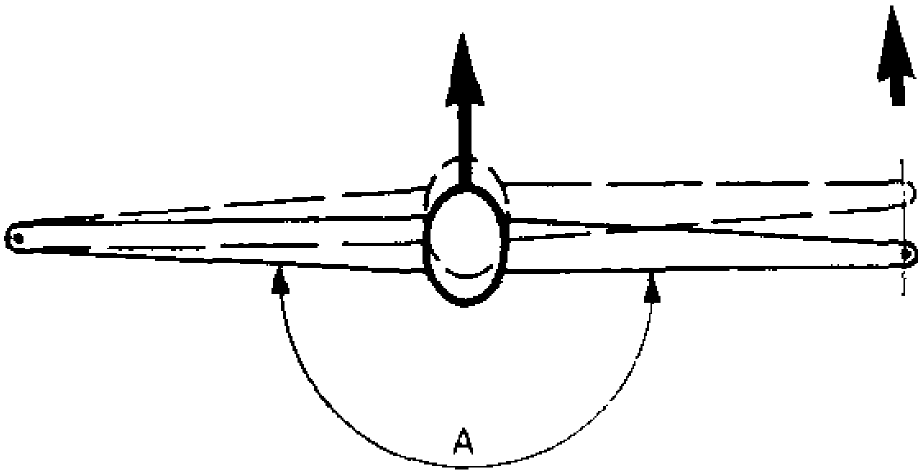


Fig. VI-11. *At the time of its bending, the mast swivels about the end of its spreader to the wind around the side-shroud until the spreader under the wind tightens its stay and takes support there. The modification of the angle of the aperture of the spreaders 'A' makes it possible to regulate the bend of the mast by letting the spreader develop load more or less before the shroud intervenes.*

The shape that the mast will take will result from the balance between mainsail loads and the reaction to the bending of the mast itself.
The distribution of the loads of the mainsail itself will depend on the deformations applied to the sail because of the cut of the sail and its adjustment, while the reactions of the mast will be a function of the evolution of its section in its various parts.

The behaviour of the 3/4 or 7/8 rig of a racing yacht will be similar to that of the light centre-board yacht where the load of the forestay-halyard is not balanced essentially by the mainsail but more generally by the running backstay, so that one has more means to control the bending of the mast: lower-shroud, backstay, check stay, jumper (fig. VI-12), the last two having a particularly direct action on the form of this bending, the check stays controlling the bend between the rigging of the forestay and the deck, the jumper that ranging between the top spreader and the head.

In addition to the deflection and compressive stresses which we have just analysed, a mast will be subjected to torsional stresses resulting from the forces of the mainsail, the boom and, generally, rigging are applied to the periphery of its section. Although the torques which result from it are weak they cannot be ignored, at least at the stage of the design.

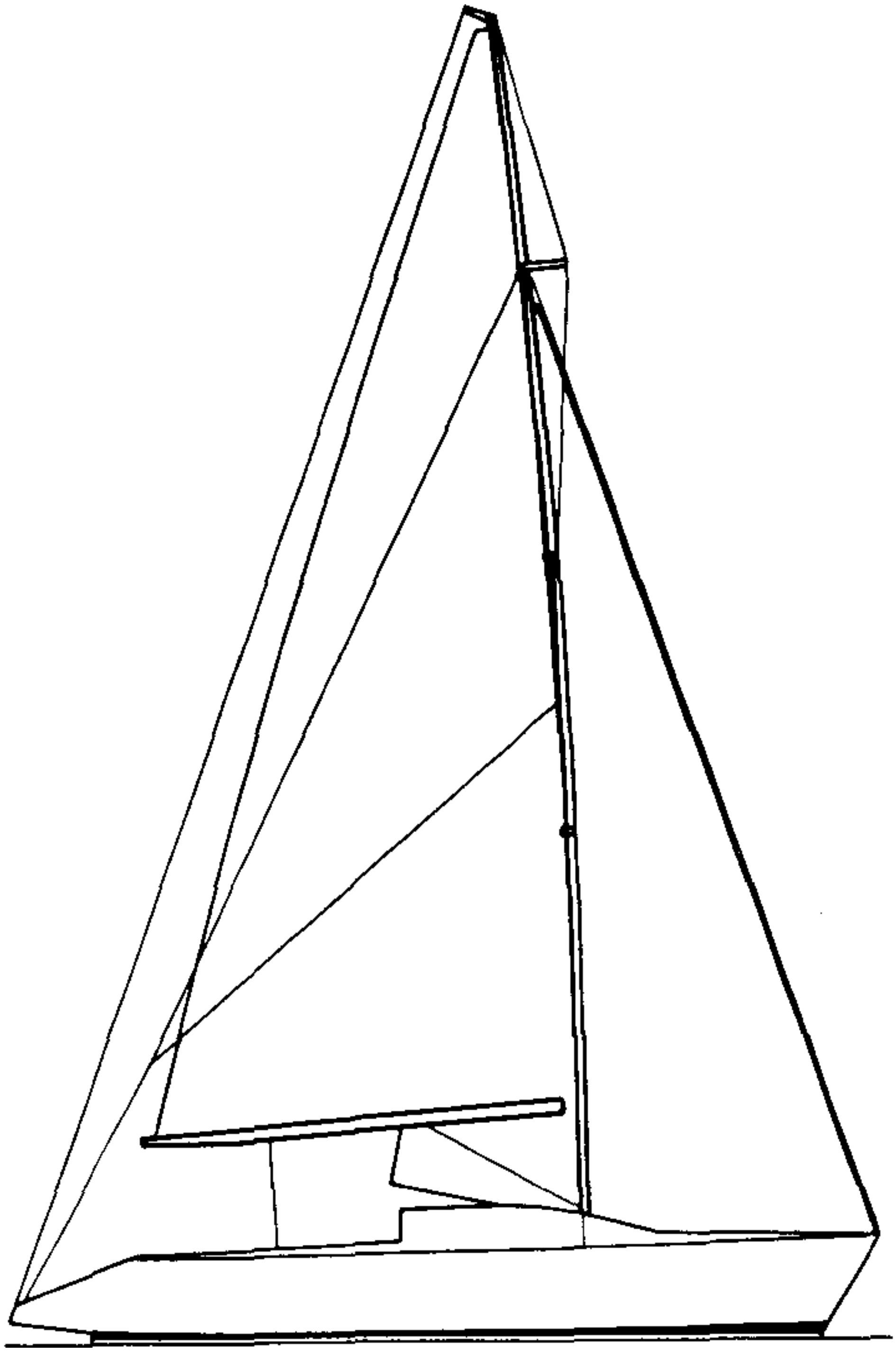


Fig. VI-12. *With fractional rigging the mainsail only partially balances the load of the forestay, this role being especially filled by the running backstay. One can then have many means of controlling the bend of the mast: as a whole by the backstay, in its higher part by the jumpers and in its lower part by the check stay.*