

PRELIMINARY EVALUATION OF AXIAL COMPRESSION FORCE ON THE MAST

First of all let's make a bit of an introduction perhaps useful to clarify the issue

The existing methods for mast and rigging calculation are based on the determination of the maximum compression load acting on the mast being a function of the boat Righting Moment.

The ISO guide lines state as follows:

..For large sailing multihulls, the righting moment is so huge that it would not be realistic to assess the load on rig by equating heeling and righting moment. Therefore for multihulls, the design heeling moment is taken when the first reef is taken, as calculated in ISO 12217-3, unless the boat is stated by its manufacturer to be designed to "fly a hull".....

.....well.....we will consider it asjust flying the windward hull !.....as this situation is most likely to occur on a regular basis on racing multi-hulls and many cruising multi-hulls as well.

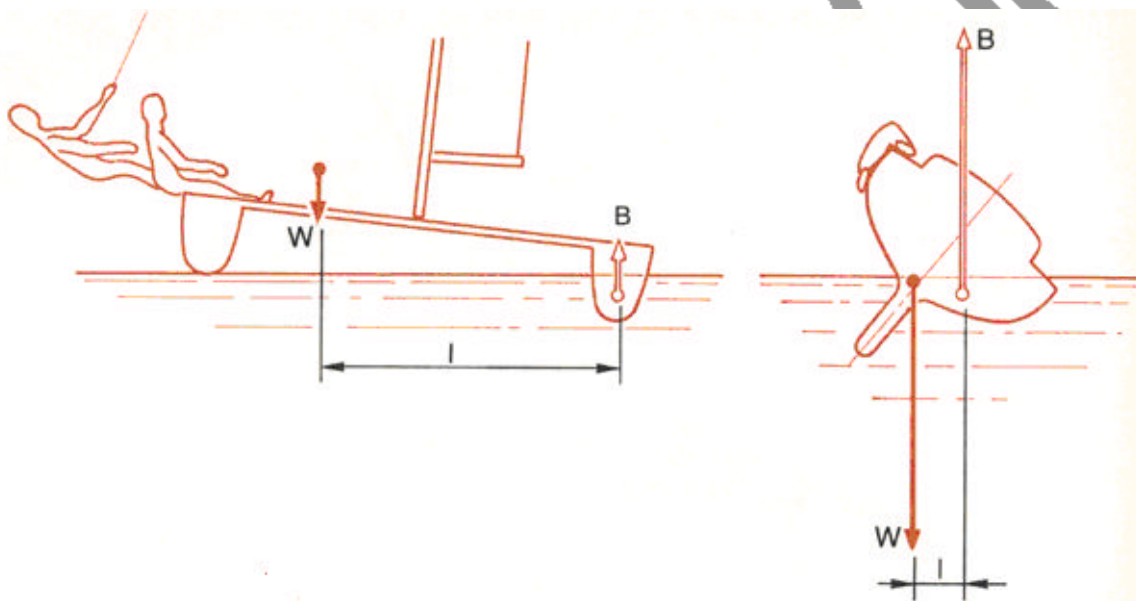


Figure extracted from Pierre Gutelle, "The Design of Sailing Yachts", (International Marine Publishing, first edition, 1979), showing the difference in Righting Moment, where, even on small angles of heel, multihulls will face a maximum load much more frequently than a monohull will do.

Hence, the main problem encounter with a multihull is that it has a very high Righting Moment if compared with a monohull even at smaller angles of heel and it obviously reaches the maximum as soon as the windward hull rises fully out of the water, as previously stated.

This aspect must be considered in the evaluation of a mast compression load.

As a result, the dimensions of the mast section has to be considerable larger in respect of the vessel size as well as the wall thickness which has to be a lot thicker on a multihull rather than for a monohull. On the other hand, a multihull, by virtue of its width, has a much broader staying base than a monohull so that high loads in rigging are mitigated somewhat by the angles the shrouds and stays make to the mast. This has a modifying effect on the compression in the mast, allowing the mast to be made somewhat lighter and, therefore, cheaper to build than one would otherwise expect, considering the high Righting Moments involved.

An aluminum stayed mast is a reasonable lightweight and cheap option.

Just to give the idea of a computational procedure involved in the calculation of the compression force along a standard mast, taking into account a **Knock-down by Spinnaker** (which is slightly simpler than main+genoa) could be itemized as follows:

First of all, make some realistic assumptions, for the case considered, such as:

- a. Max RM occurring @ **20° (JUST FOR MULTIHULLS)** though max stability can be approximated by multiplying **0.50** by the beam between centerlines of outer hulls (assumed in the region of **8,5m**), or **0,75** by the Bmax for narrow cruisers or up to **0,90** by the Bmax for wide racers, times, or better saying, ..multiplied the displacement.
- b. LOA and Bmax assumed being = **10m** approx.
- c. Max Width between chain plates assumed to be about **9.0m (i.e. 0,9*Bmax)**
- d. Halyards compression due to main **1/5** of max BL and due to staysail is **2/5** of max BL. (a tot of 60% of nominal Breaking Load to be added on to the mast tot vertical axial compression load).
- e. Add on to point (d) also the allowance for 180° pulley friction (i.e. multiply by **1,85** correction factor the halyards compression load)
- f. Consider the approximate mast weight being of about **14 kgm** (weight per unit length)
- g. Add on an allowance to mast weight to incorporate fittings weight i.e. **1,25** (a multiplying factor of the mast weight)
- h. Consider the $RM_{20^\circ} \cong 18 * RM_{1^\circ}$ (quite realistic for a trimaran of around **10m**, a LOA value assumed being quite reasonable for a modern wide cruiser/racers for a given W_{mass} of about **2500kg**)
- i. Reasonable initial GM_T for trimaran hulls of about **10m** could be considered in the region of about **13-14m.**, slightly higher than the Open 60 monohull yachts wide model size.
- j. Halyards (galvanized steel flexible wire) reasonable dimension is \cong **6mm** for a 10m vsl approx., having a nominal Breaking Load of **2300 kg** \approx .
- k. Distance from masthead (halyard pulley) to CLR assumed to be **16.5m** approx.
- l. Mast height. **15m** approx
- m. Angle between shrouds and top of mast \approx **16°** ; angle between forestay and mast \approx **19°** ; angle between mast and shrouds on the longitudinal plane \approx **10°** .
- n. No pre-tension on rig.

N.B. ASSUMING NO SPREADERS ARRANGEMENTS - (not an optimum solution as such)

1	RM_{1°	$= \frac{W_{(displ.mass)} * GM_T}{57.3} * \phi = \frac{2600 * 13.5 * 1^\circ}{57.3}$	=	613 kgm
2.	RM_{20°	$= 18 * 613$	=	11000 kgm \approx
3.	MAST wt / unit length	Approx rigged mast weight /m incl. fittings: $P=14*1.25$	=	17.5 kg/m
4.	Halyards compression acting axially along mast	Compression due to staysail+main as a percentage of max BL i.e. 60% of 2300 (max Breaking Load)	=	1380 kg
5.	Pulley Friction	allowance for 180° pulley friction $P_2 = 1380 * 1.85$	=	2550 kg
6.	load at SPI halyard attachment normal to mast	$P_{T1} = \frac{RM_{20^\circ}}{(height\ masthead\ to\ CLR)} = \frac{11000}{16.50}$ (normal to the mast)	=	667 kg
7.	total mast weight	applied normal to the mast at the masthead $17.5 * 15$	=	263 kg
8.	Mast weight load component (i)	Applied @ the masthead (and normal to the mast) $P_{T2} = 263 * \cos 20^\circ$	=	247 kg \approx
9.	load P_T normal to mast	$P_T = P_{T1} + P_{T2} = 667 + 247$ (due to mast weight)	=	914 kg \approx

10	shroud tension T	$T = \frac{P_T}{\sin 16^\circ} = \frac{914}{0.28} =$	3316 kg
11	axial load on mast	$P_1 = T * \cos 16^\circ = 3316 * 0.96 =$	3188 kg
12	TOT axial vertical load on mast	$P = P_1 + P_2 = 3188 + 2550 =$ (quite reasonable result for this vs! LOA and the type of rig envisaged !)	5738 kg
13	Minimum required Mom of Inertia I _{XX} - (ii)	$= P * K_1 * K_3 * L^2 * 10^{-7} = 5738 * 2.4 * 1.35 * 1500^2 * 10^{-7} =$	4183 cm ⁴
14	Minimum required Mom of Inertia I _{YY} - (iii)	$= P * K_2 * K_3 * L^2 * 10^{-7} = 5738 * 2 * 1.35 * 1500^2 * 10^{-7} * 1.9 =$	6623 cm ⁴
15	<p>From SPACRAFT std catalog we choose the PERFORMANCE Range Mast - F4600 - giving</p> <p>DUE TO AN EXTREMELY HIGH VALUE OF I_{YY} IT IS HIGHLY ADVISABLE TO CONSIDER A TAPERED MAST.</p> <p>The dimensions being</p> <p>and</p>		<p>I_{XX} I_{YY}</p> <p>4400 cm⁴ 12600 cm⁴</p> <p>along the XX axis along the YY axis weight per unit length</p> <p>223 mm 400 mm 18 kg/m</p>

- (i) the mast is considered as having a single panel neglecting the UDL when calculating P the "critical load" applied normal to masthead, as no spreaders are fitted onto the mast
- (ii) K₁=panel factor =2.4 (for no spreaders rig)
K₃=factor for deck stepped mast=1.35
L=actual panel length (in our case mast head +no spreaders rig means tot mast height to be taken for calculation)
- (iii) K₂=staying factor=2 (for no spreaders rig)
K₃=factor for deck stepped mast=1.35
L=actual panel length (in our case mast head +no spreaders rig means tot mast height to be taken for calculation)
1.9=factor of safety

....."Furthermore it is important to underline that in the classification societies construction rules as "Bureau Veritas Rule" or "Rules for construction of vessel less then 15 metres (1983)" of Det Norske Veritas there are also rules for mast scantlings determination. These methods are based on simplified models of structural behaviour coupled to certain assumptions involving loadings and allowable stresses, tempered by a knowledge of mast failures in service....." (Sailing Yacht Design: Theory - 1998)

The most popular method used is without any doubt:

SKENE'S METHOD

The critical load P_T at the basis of the mast is calculated from the RM_{30°}

$P_T = \frac{1.5 * RM_{30^\circ}}{0.5 * b}$; therefore the Maximum Compressive Load $P = 1.85 * P_T$ where:

- RM_{30°} = righting moment at 30° heel
- b = lower shroud spreading (or chain plate width)
- 1.50 = allowance for heeling angles >30°
- 1.85 = factor of safety for stays, halyards and sheeting

The minimum required moment of inertia in cm⁴ for the mast section is given by the following formula:

$$I_{MIN} = 1.422 * C * P * L^2 * 10^{-7} \text{ [cm}^4\text{] where:}$$

C = is a coefficient used depending on the mast panel, mast step, n° of spreaders and type of rig as per the table below (assuming per default the mast material being aluminum)

panels	Mast step	athwartship		longitudinal		
		Sing. spreader	2/3 sets of spreaders	Masthead rig		7/8 fore triangle
				Short	Tall	
Lower panels	Keel stepped	12.9	15.1	7.6	8.0	7.2
Upper panels	Deck stepped	16.2	19.4	8.3	9.4	8.9
		20.9	23.3			

P = Maximum Compressive Load in (kg)

L² = actual mast panel length considered from mast deck step to first set of spreaders (if any...) in cm

For the shrouds scantling, the load distribution, derived from experimental measurements, can be assumed as a percentage of the critical load P_T with a FS = 3.

<p>Test for P value obtained using Skene's formula (iv)</p>	$P = \frac{(0.87 * 11000) * 1.5 * 1.85}{0.5 * 9.0}$ <p>RM_{30°} = 87% of max RM (i.e. RM_{20°} for multihulls)</p>	<p>5900kg ≈ (3% ≈ difference between results)</p>
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- (iv) 1.5=safety factor used as allowance to RM_{30°}
- 1.85=allowance for stay-backstay and running rigging
- Max chain width ≈ 9.0m (i.e. 0,9*Bmax)

N.B.

If hydrostatic characteristics are not available there is a formula proposed by **Dr Gerritsma (1993)** which can be useful in obtaining a preliminary value of the Righting Moment as follows:

$$M_R(\phi) = \Delta \left[\left(0.664T_C + 0.111 \frac{BWL^2}{T_C} - G_{DWL} \right) \sin \phi + LWL(D_2 * \phi * F_N + D_3 * \phi^2) \right]$$

Where:

- Δ = displacement of the vessel
- T_C = draught at canoe body
- B_{WL} = breadth water line
- G_{DWL} = center of gravity of the yacht (-ve if above DWL)
- φ = heel angle
- L_{WL} = length waterline

$$D_2 = -0.0406 + 0.0109 * \left(\frac{B_{WL}}{T_C} \right) - 0.00105 * \left(\frac{B_{WL}}{T_C} \right)^2 \quad \text{a stability coefficient}$$

$$F_N = \frac{V_S}{\sqrt{g * L_{WL}}} \quad \text{Froude Number}$$

$$D_3 = 0.0636 - 0.0196 * \left(\frac{B_{WL}}{T_C} \right) \quad \text{a stability coefficient}$$

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N.B. when considering knock down by main+genoa the procedure is slightly different !

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