Section 1

Design and Construction of Large Modern Yacht Rigs

A. General

1. Scope

1.1 These guidelines generally apply to sailing yachts of **L** > 24 m, under the condition, that the yacht is handled correctly in terms of good seamanship.

1.2 These guidelines are generally applicable for bermudian rigs with spars made of carbon fibre reinforced plastics or aluminium alloy.

1.3 The principles presented in the following are to be used as a general guidance. Any detailed analysis which is leading to different reserve or reduction factors can be submitted on the basis of an equivalent safety.

1.4 Scope of these guidelines are the structural integrity of one- or multiple-masted, bermudian rigged sailing yachts including the dimensioning of standing rigging, mast and boom sections as well as local construction in way of fittings structurally attached to the spars.

2. Documents to be submitted

Relate to Annex A for the scope of documents and information required for certification.

B. Design and Construction Principles

1. General

1.1 Generally, the basic value for all following evaluations is the static righting moment (RM) of the yacht at full displacement with a heel angle corresponding to SWA.

1.2 The "Safe Working Angle (SWA)", which will be referred to in the following, generally represents a heeling angle of 30°. However, other angles may be defined as SWA in agreement with GL. GL reserves the right to assess the SWA according to the relevant characteristics of the yacht under sail according to Table 1.1.

2. Load cases

2.1 Ordinary sailing conditions

Upwind beating, reaching and broad reaching under appropriate sail configurations for light, moderate, strong and stormy wind conditions, such as:

– full main, working jib, genoa I or reacher
– several reef stages main, working jib, reefed jib, stay sail
– spinnaker only
– others and special configurations for special rigs

Table 1.1 Yacht characteristics

Category	Displacement Characteristics	Typical Purpose Characteristics	Typical Handling Characteristics
I	Motor Sailer/ Heavy Cruiser	Ocean Going	Handled by owner / crew
II	Mid Displacement	Offshore	Short-handed
III	Light Displacement	Coastal pleasure cruises / Club Racing	Short-handed or handled by crew
IV	Ultra Light Displacement	Racing	Handled by professional crew

2.2 Extreme conditions

Extreme conditions may need to be defined in special cases, depending on the boat size and other configurations.

3. Generation of rig loads

3.1 Pretensioning of rig

The pretensioning of the rigging is to be specified by the designer, otherwise pretensioning is set to avoid slack leeward cap shrouds, when sailing at heeling angles smaller than the "SWA".

3.2 Transverse sail forces

Transverse forces are generated from righting moment:

Each sail's contribution to the resultant heeling moment is assumed to be proportional to the sail's area and the distance of its centre of effort above the underwater body's centre of lateral resistance, see Fig. 1.1. The sum of these heeling moments is set equal to the vessel's righting moment under the conditions and specific sail configurations being evaluated:

Transverse force from mainsail:

$$F_{tm} = \frac{RM_{Design}}{\overline{CoE_m CLR} + \frac{A_f}{A_m} \cdot \overline{CoE_f CLR}} \quad [N]$$

Transverse force from foresail:

$$F_{tf} = \frac{A_f}{A_m} \cdot F_{tm} \quad [N]$$

Transverse force from spinnaker when "broaching".

$$F_{ts} = \frac{RM_{Design}}{\overline{CoE_s CLR}} \quad [N]$$

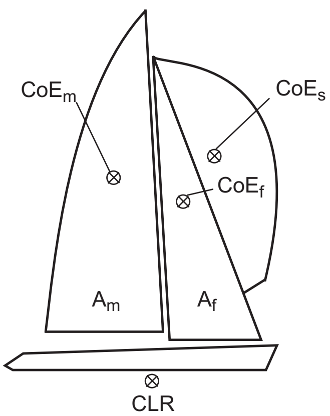


Fig. 1.1 Centres of effort

RM_{Design} = righting moment as defined in B.1. [Nm]

$CoE_{m/f/s}$ = centre of effort of respective sail:

CoE_m = 0,39 P above gooseneck [m] (default)

CoE_f = 0,39 I above foot [m] (default)

CoE_s = 0,59 I above deck [m] (default)

CLR = The centre of lateral resistance of the underwater body (including appendages) [m]

A_m = mainsail area, projected laterally [m2] 1

Af = foresail area, projected laterally [m2] 1

P = mainsail hoist [m]

E = foot of mainsail [m]

I = height of fore triangle [m]

J = base of fore triangle [m]

3.2.1 Estimation of corresponding apparent wind speed for upwind cases

$$v_a = \sqrt{\frac{F_{t(m/f)}}{SFC \cdot A_{m/f} \cdot 0,5 \cdot \rho}} \quad [m/s]$$

SFC = 1,2 (side force coefficient)

ρ = density of air [kg/m^3]

3.2.2 Distribution of transverse sail forces of the mainsail

A set of point loads is to be calculated from F_{tm} acting on the mast as shown in Fig. 1.2. The point load distribution must be appropriate for the specified sail configuration and must of course reproduce the equilibrium of moments. Table 1.2 shows examples of such point load distributions.

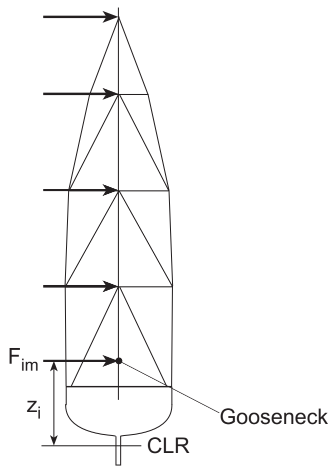


Fig. 1.2 Mainsail load distribution

1 Sail areas may be corrected by multiplication with factors of efficiency, depending on the specific sail configurations, e.g. full main combined with 100 % foretriangle jib:

$$C_m = 0,9, \quad c_f = 1,1$$

Table 1.2 Approaches for mainsail load distribution

	c_{im}		
	3-spreader-rig	**4-spreader-rig**	**5-spreader-rig**
clew [1]	(0,25)	(0,25)	(0,25)
gooseneck, tack	0,0	0,0	0,0
spreader 1	0,05	0,0	0,0
spreader 2	0,15	0,05	0,0
spreader 3	0,25	0,15	0,05
spreader 4	—	0,25	0,15
spreader 5	—	—	0,25
main headboard	0,30	0,30	0,30

[1] not applied on rig explicitly

$$F_{im} = c_{im} \cdot F_{tmd} \text{ [N]}$$

$$F_{tmd} = \frac{F_{tm} \cdot \overline{CoE_m CLR}}{\sum_{i=1}^{n} (c_{im} \cdot z_i)} \text{ [N]}$$

F_{tm} = transverse force mainsail according to 3.2

c_{im} = distribution factor with:

$$\sum_{i=1}^{n} c_{im} = 1$$

3.2.3 Distribution of transverse sail forces of the foresail

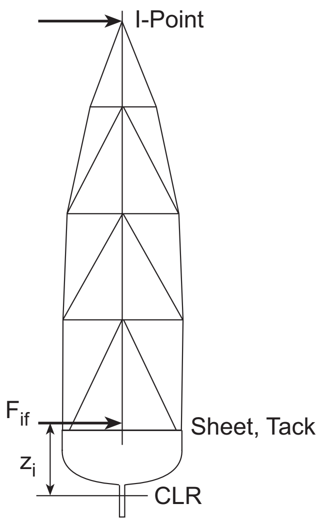


Fig. 1.3 Foresail point loads

$$F_{if} = c_{if} \cdot F_{tfd} \text{ [N]}$$

$$F_{tfd} = \frac{F_{tf} \cdot \overline{CoE_f CLR}}{\sum_{i=1}^{3} (c_{if} \cdot z_i)} \text{ [N]}$$

F_{tf} = transverse force foresail according to 3.2

c_{if} = distribution factor with:

$$\sum_{i=1}^{n} c_{if} = 1$$

Table 1.3 shows an example of the foresail load distribution.

Table 1.3 Approach for foresail load distribution

	c_{if}
tack [1]	(0,3)
clew [1]	(0,3)
head	0,4

[1] not applied on rig explicitly

3.2.4 Distribution of transverse sail forces of the spinnaker

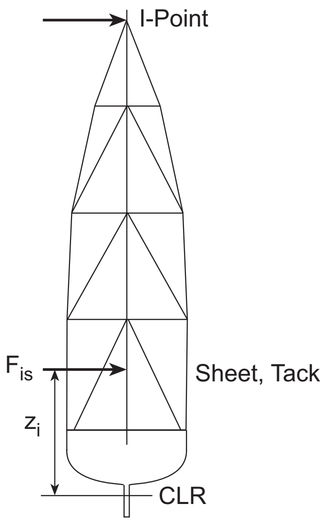


Fig. 1.4 Spinnaker point loads

$$F_{is} = c_{is} \cdot F_{tsd}\,[N]$$

$$F_{tsd} = \frac{F_{ts} \cdot \overline{CoE_s CLR}}{\sum_{i=1}^{3}\left(c_{is} \cdot z_i\right)}\;[N]$$

F_{ts} = according to 3.2

c_{is} = distribution factor with:

$$\sum_{i=1}^{n} c_{is} = 1$$

Table 1.4 shows an example of spinnaker load distribution.

Table 1.4 Approach for spinnaker load distribution

	c_{is}
tack [1]	(0,3)
clew [1]	(0,3)
head	0,4

[1] not applied on rig explicitly

3.3 Multiple-mast rig

For a multiple-mast rig a conservative assumption of the proportioning of righting moment is to be made:

For all relevant sail configurations, the fractions of sail area moments (SAM) for each mast from the total SAM have to be determined to find the design righting moment for each mast.

The sail area moment is defined as:

$$SAM = A \cdot \overline{CoE\ CLR}\;\left[m^3\right]$$

The sail area moment for each mast is defined as:

$$SAM_i = \sum_{j=1}^{n}\left(A_j \cdot \overline{CoE_j\,CLR}\right)\;\left[m^3\right]$$

i = index for specific mast

j = index for specific sail on specific mast

The fraction of each mast from the total sail area moment is defined as:

$$f_i = \frac{SAM_i}{\sum_{i=1}^{n} SAM_i}$$

The design righting moment RM_{design} for each mast is to be determined as follows:

– For a mast with a max. fraction f between 100 % – 67 %:

RM_{design} = 1,0 · (RM at SWA)

– For a mast with a max. fraction f between 67 % – 30 %:

RM_{design} = 1,5 · f · (RM at SWA)

– For masts with max. fractions f < 30 %:

RM_{design} = overturning moment (OTM) due to app. wind speed with twice the value determined according to 3.2.1.

Windage of masts and rigging (and equipment) and therewith contribution to (each) SAM and/or (OTM) may be taken into account.

3.4 Self-weight

Self-weight of a rig induces additional inner forces in transverse standing rigging and mast.

The magnitude of overturning moment due to the self-weight must be correlated with the righting moment of the yacht, both at the safe working angle (generally 30°). When the overturning moment of the rig exceeds the fraction of 20 % of the righting moment, the self-weight effect is to be taken into consideration.

3.5 Extreme loads

Extreme loads can be defined in each separate case, depending on special configurations.

4. Determination of working loads of running and standing rigging

4.1 Running rigging

The following approaches are to be seen as a general estimation of an initial calculation value. Care has to be taken, when configurations require modified approaches.

4.1.1 Halyards

The working load of a halyard is generally generated by membrane forces in a sail. Its magnitude depends on the amount of sag of the leech including a preload due to hoisting. Determination of the halyard load is to be based on design righting moment and the following sail configuration:

Full main and 100 % foresail (i.e. the foresail foot length equals J).

4.1.1.1 Mainsail and/or mizzensail halyards:

$$F_{mhy} = 1,08 \cdot F_{ml} \cdot f_r \quad [N]$$

F_{ml} = mainsail leech load

$$= \frac{F_{tm}}{8 \cdot s} \quad [N]$$

f_r = roach factor

$$= \frac{A_m}{0,5 \cdot P \cdot E}$$

F_{tm} = according to 3.2

s = sag fraction

= 0,085 [–], (8,5 % of leech length) for category I, II, III

= 0,065 [–], (6,5 % of leech length) for category IV

4.1.1.2 Foresails (genoa, jib, staysail, etc.) halyards

$$F_{fhy} = 1,02 \cdot \frac{F_{tf}}{8 \cdot s} \quad [N]$$

F_{tf} = according to 3.2

s = sag fraction

= 0,045 [–], (4,5 % of leech length)

4.1.2 Boom outhaul

The force of the outhaul is generated by the horizontal component of the leech load and a force resultant from the sag of the sail foot.

$$F_{oh} = \sin\left(\arctan\left(\frac{P}{E}\right)\right) \cdot F_{ml} + F_{tm} \cdot \frac{E}{P \cdot 8 \cdot 0,05} \quad [N]$$

F_{ml} = according to 4.1.1.1

F_{tm} = transverse force from mainsail according to 3.2

4.1.3 Mainsheet

The working load of the mainsheet is estimated by a given sag of the leech. Its vertical component F_{msv} is calculated by the formula:

$$F_{msv} = \frac{E}{X_{ms}} \cdot F_{ml} \quad [N]$$

X_{ms} = sheet attachment point on boom aft of gooseneck [m]

F_{ml} = according to 4.1.1.1

4.1.4 Vang

The maximum vang loads normally occur when reaching or running downwind. Base value for calculating the vang load is again the leech load of the mainsail which in turn is determined by the sag fraction specified below. By omitting the mainsheet load contribution the following formula for the vang load Fv results from force equilibrium according to Fig. 1.5.

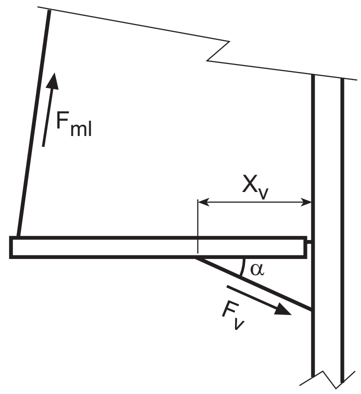


Fig. 1.5 Vang load determination

$$F_v = \frac{F_{tm}}{8 \cdot s} \cdot \frac{E}{x_v \cdot \sin\alpha} \quad [N]$$

F_{tm} = according to 3.2

x_v = distance from gooseneck to boom vang fitting [m]

α = angle between vang and boom

s = sag fraction

= 0,25 [–], (25 % of leech length) for category I, II

= 0,20 [–], (20 % of leech length) for category III

= 0,15 [–], (15 % of leech length) for category IV

4.1.5 Spinnaker pole

Normally, the maximum working compression of the spinnaker pole occurs under tight reaching condition, when the spinnaker pole points straight forward. The load induced is assumed to be generated by an interaction between afterguy and pole according to Fig. 1.6.

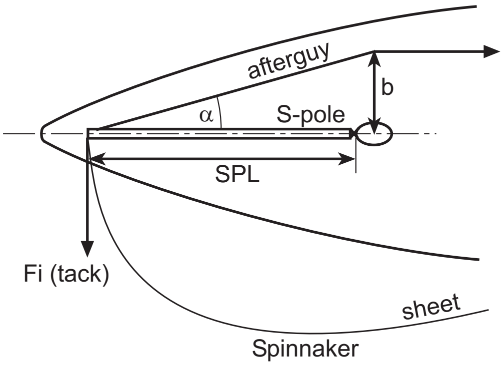


Fig. 1.6 Spinnaker pole force

Maximum working compression of spinnaker pole:

$$F_{sp} = \frac{F_{tack}}{\tan\alpha} \quad [N]$$

F_{tack} = relevant F_{is} according to 3.2.3

α = $\arctan\left(\frac{b}{SPL}\right)$

b = distance of deflection sheave from centre line or length of jockey pole [m]

It is to be considered whether a supplement has to be made due to sheet loads (for rather flat spinnakers or gennakers).

4.2 Standing rigging

GL examines standing rigging sizes by calculating working loads and correlate them with the reserve factors according to 5.1. Calculation method is geometric non-linear finite element analysis.

Note

Working loads of longitudinal stays can be determined analytically (see 4.2.2).

4.2.1 Shrouds

Calculation of shroud working loads is to be based on the input specified in 3.

4.2.2 Head stays

The working load is the resultant axial force due to sag of a sail-carrying headstay.

The sag is the maximum transverse deflection of a line under a lateral uniform load between its end points.

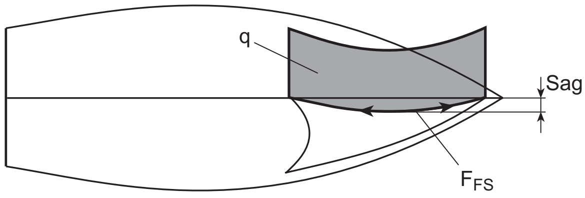
The values specified below are relevant for the load case of a full main combined with a jib of 100 % forestay-triangle area or reefed main combined with staysail at SWA. The lateral load q is a uniform load equivalent to the force F_{tf} defined in 3.2.2, see Fig. 1.7.

Headstay working load F_{hs}:

$$F_{hs} = \frac{q \cdot l_0}{8 \cdot s} \quad [N]$$

$$q = \frac{F_{tf}}{l_0} \quad [N/m]$$

l_0 = stay length [m]



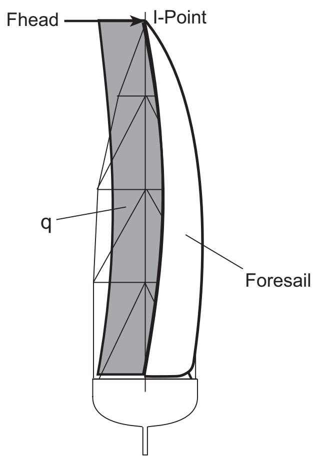


Fig. 1.7 Headstay load

s = the magnitude of sag "s" as a fraction of the stay length is not to be taken more than according to Table 1.5:

Table 1.5 Headstay sag

	sag			
	Cat. IV (preliminary)	**Cat. III**	**Cat II**	**Cat. I**
jib	0,7 %	1,0 %	1,5 %	2,0 %
staysail	1,5 %	2,5 %	3,0 %	5,0 %

Deviations from these indexes can only be considered in well-founded cases, resulting from exceptional sail and/or design characteristics.

Working loads for non-sail-carrying headstays (inner forestays, baby stays) are not explicitly specified here. In this case, design criterion is the rig's required longitudinal stiffness dealt with in 5.2.

4.2.3 Backstay(s):

For masthead rigs, backstay design load is obtained by opposing the forestay design load under equilibrium of moments about the mast base. In case of swept spreaders a contribution of cap shrouds may be considered.

4.2.4 Runners, check stays, etc.

Runner and/or check stay design loads are obtained by opposing the forward longitudinal stays design loads under equilibrium of moments about the mast base.

Besides, runners may be necessary not only to control but also to support and stabilise the rig, see 5.2.

5. Global Analysis

5.1 Standing rigging

5.1.1 General

Diagonal shrouds shall generally have a minimum angle to the mast centreline of 9°. If spreaders are swept , they shall be swept evenly, so that all shrouds are in plane on either side, when rig is unstressed. Spreader sweep angles between 5° and 9° are not advisable.

The reserve factors (RF) are valid provided working loads in standing rigging have been calculated by static, geometric non-linear analyses.

5.1.2 Transverse rigging

RF ≥ 2,9 versus working loads determined according to 4.2.1.

RF ≥ 2,5 versus working loads determined according to 4.2.1 including the self-weight effect

Besides, global rig stiffness has to be considered, since in case of swept spreaders the "system stiffness" of the rig is also influenced by the dimensions and geometric arrangement of transverse rigging.

5.1.3 Fore and aft rigging, others

RF ≥ 2,0 versus design load according to 4.2.2, 4.2.3, 4.2.4

RF ≥ 2,5 versus design load according to 4.2.2, 4.2.3, 4.2.4 for soft aramid rigging and generally for Category I yachts

5.2 Stability analysis

The following stability evaluations are based on the determination of buckling modes. The reserve factors versus buckling do not necessarily represent a safety against the occurrence of this failure mode, because the applied method assumes ideal straightness of the mast and its alignment with the forces which is not the case in the realistic situation. Yet, the method provides a measure for assessing the rig's stiffness.

5.2.1 Global stability and stiffness

Longitudinal buckling of the whole rig-system fore and aft. The following reserve factors are applicable for an evaluation according to the "Euler Eigenmode" method. The determination of mast compression levels is based on static, non-linear analysis.

RF ≥ 3,4 versus each set of mast panel compressions resulting from all relevant working loads according to 4.

RF ≥ 3,1 versus each set of mast panel compressions resulting from all relevant working loads according to 4. including self-weight effect according to 3.4

Global stiffness must also be considered in case the yacht is driven with no mainsail, e.g. under engine, against heavy seaways.

5.2.2 Local stability and stiffness

Transverse buckling of the mast normally occurs as "panel-buckling" between transverse supports. Reserve factors are again applicable for an evaluation according to the "Euler Eigenmode" method.

RF ≥ 2,9 versus each set of mast panel compressions resulting from all relevant working loads according to 4.

RF ≥ 2,6 versus each set of mast panel compressions resulting from all relevant working loads according to 4., including self-weight effect according to 3.4

5.2.3 Shear stiffness of CRP-mast tubes

25 % (by weight) of the mast's basic laminate lay-up shall have ± 45° fibre orientation to achieve a minimum shear stiffness. A stiffness correction of this content is to be taken into account in case of dissimilar moduli of fibres running in 0° and 45°.

Also refer to C.1.3 for minimum elastic properties of tubes.

However special considerations are required for furling masts with open sections.

5.2.4 Thin wall buckling of the tube:

Tube wall buckling has to be considered.

RF ≥ 3,0 versus ultimate buckling stress or strain according to max. working compression in each wall panel resulting from load case acc. to 2.1 (reserve factors are applicable for Roark and Young’s theory of skin buckling under compression loads for curved, non-isotropic plates). Load concentrations are to be considered particularly in way of:

– mast step, especially when the mast can not be pitched

– D-tangs

5.3 Spreader construction

Spreaders are subjected to axial, bending and shear loads. Each of the following scenarios described in 5.3.1 to 5.3.4 is to be considered. Proof of sufficient safety is based on "first principles" of engineering. In Figures 1.8 and 1.9 relevant arrangements and coordinates are shown. Relevant allowable strains and stresses are defined in 9.1.2, 9.1.3 and 9.1.4. The design loads are to be determined as follows:

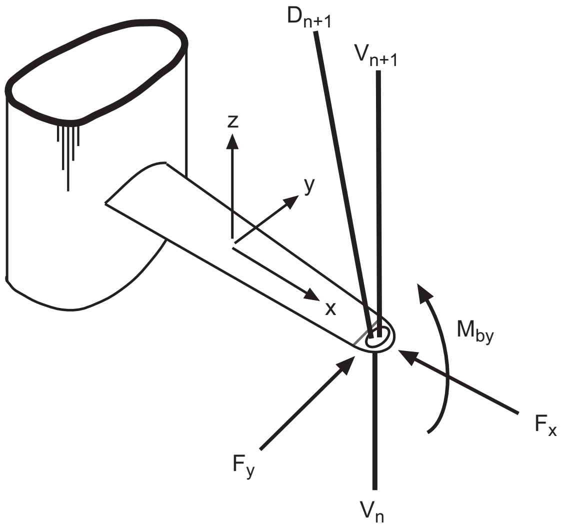


Fig. 1.8 Forces on apreader

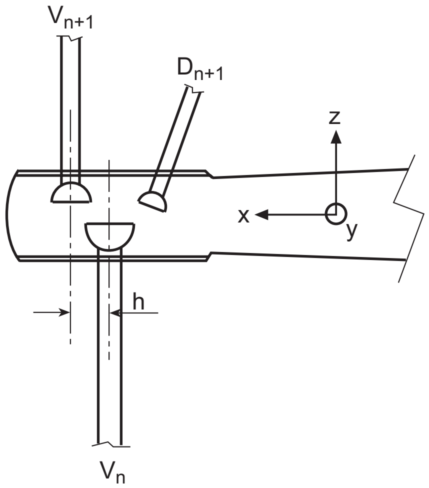


Fig. 1.9 Spreader end detail

5.3.1 Loading on windward side

F_{xa} = load in x-direction, resulting from relevant components of shroud breaking loads (V_n, V_{n+1}, D_{n+1}) [N]

or

F_{xb} = load in x-direction, resulting from relevant components of 3 times the calculated shroud working loads [N]

M_{by} = bending moment resulting from breaking loads of V_{n+1} with an offset of h (tip cup offset) [Nm]:

- for Navtec 528 Standard:
  Tip cup offset = 0,6 × diam. V_{n+1}
- for Navtec 534/834:
  0,5 × diam V_{n+1}
- for others: to be specified

F_{ya} = load in y-direction at spreader tip generated by mast bent ($F_{ya\ max}$ on windward side):

$$= V1_{BL} \cdot 0,0055 \cdot k_1 \cdot k_2 \quad [N]$$

$V1_{BL}$ = nominal break load from V1 [N]

k_1 = 0,7 for non-swept spreaders

= 1,0 for 20° spreader-rake, interpolate in-between

k_2 = distribution factor according to Table 1.6

or

F_{yb} = sectional loads in y-direction F_y at spreader tips obtained from finite element analysis (FEA)

= $2 \cdot F_y$ from FEA [N]

The sectional loads in the spreaders are combinations from design loads listed above.

Table 1.6 Distribution factors

k_2	3-spreader-rig	4-spreader-rig	5-spreader-rig
Spreader 1	0,7	0,6	0,6
Spreader 2	1,0	0,9	0,8
Spreader 3	0,95	1,0	1,0
Spreader 4	—	0,96	0,95
Spreader 5	—	—	0,85

5.3.2 Loading on leeward side

F_{yc} = loads from mainsail pushing against each leeward spreader

$$= l_p \cdot E \cdot c_1 \cdot c_2 \cdot c_3 \cdot 0{,}6 \cdot v_{aws}^2 \quad [N]$$

$$l_p = \frac{P}{n+1} \quad [m]$$

n = number of spreaders

P = lufflength of mainsail in [m]

v_{aws} = Apparent wind speed for design purpose = 19 m/s

c_1 = sail girth factor, refer to Table 1.7

c_2 = distribution factor, refer to Table 1.8

c_3 = overload factor = 2,0

E = foot length of mainsail [m]

Choosing this method, all other design loads (F_x , F_{ya} and M_{by}) are assumed to be zero.

Table 1.7 Girth factors

c_1	3-spreader-rig	4-spreader-rig	5-spreader-rig
Spreader 1	0,75	0,8	0,83
Spreader 2	0,5	0,6	0,67
Spreader 3	0,25	0,4	0,5
Spreader 4	—	0,2	0,33
Spreader 5	—	—	0,17

Table 1.8 Distribution factors

c_2	3-spreader-rig	4-spreader-rig	5-spreader-rig
Spreader 1	0,5	0,5	0,4
Spreader 2	0,8	0,7	0,6
Spreader 3	1,0	0,9	0,8
Spreader 4	—	1,0	0,9
Spreader 5	—	—	1,0

5.3.3 Spreader buckling

RF ≥ 1,1 for Euler-Buckling of spreader versus relevant design loads specified in 5.3.1

5.3.4 Spreader wall buckling

RF ≥ 1,1 for thin wall buckling of spreader versus relevant design loads specified in 5.3.1

6. Booms

Booms are subjected to compression, bending, shear and torsion primarily through the loads from sheet, leech, outhaul and vang, see Fig. 1.10.

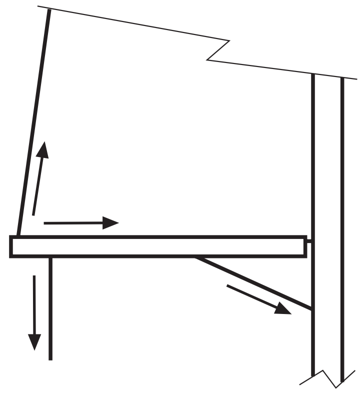


Fig. 1.10 Forces on boom

Design Loads :

1,5 × release load for max. possible relief valve setting [N]

1,0 × max. working loads of all relevant sheets, lines, outhauls etc. [N]

1,0 × M_t (resulting torsional moment), see Fig. 1.12

$$M_t = F_{sh} \cdot h + F_{sail} \cdot k \quad [\text{Nm}]$$

F_{sh} = horizontal component of mainsheet load [N], see Fig. 1.11

F_{sail} = component of mainsail load acting at mainsail clew [N], see Fig. 1.11

$$F_{sh} \approx F_{sail} = \frac{1}{3} \cdot \frac{\rho}{2} \cdot A \cdot v^2 \approx 75 \cdot A \quad [\text{N}]$$

v = apparent wind speed for design purpose = 19 m/s (35 kn)

A = mainsail area [m²]

ρ = density of air [kg/m³]

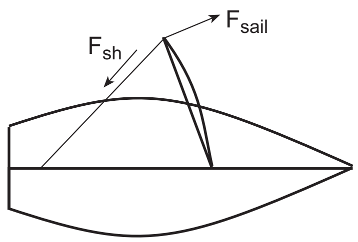


Fig. 1.11 Mainsail clew

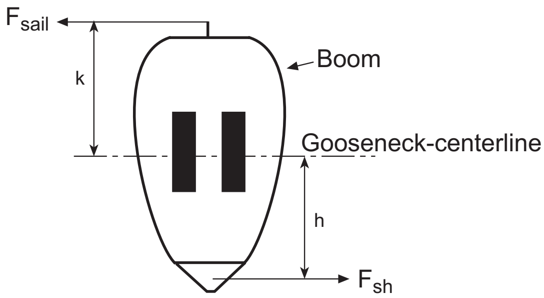


Fig. 1.12 Boom section

An appropriate combination of the above loads is to be assumed for the strength calculation.

It is strongly recommended to provide the vang with an overload relief valve. Otherwise the design load for the boom in respect of forces due to the vang has to be replaced by:

1,0 × breaking load of vang [N]

The requirements for allowable strains and stresses as defined in 9.1.2, 9.1.3 and 9.1.4 must be met when applying the design loads. Also wall buckling of the boom must be considered.

7. Mast step

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

8. Mast-panel between maststep and uppermost spinnaker pole position "(Panel 0)"

If the loading of Panel 0 due to vang, spinnaker/ jockey pole and boom has not been part of the global analysis, these loads have to be taken into account additionally when designing Panel 0. The resultant loads due to the following design loads are to be considered then:

Vang: resultant loads due to 1,5 × max. vang working-load according to 4.1.4 (for hydraulic device: vang load = release load at max. eased mainsheet).

Poles: 2 × resultant loads due to pole compression according to 4.1.5

Gooseneck: resultant loads due to 1,5 × max. vang load (for hydraulic device: vang load = release load at max. eased mainsheet plus other relevant contributions (outhaul, mainsheet etc.)).

9. Local analysis

9.1 Local analysis of components made of multi-axial-carbon fibre laminate or aluminium alloy

The reduction factors and allowable material strains and stresses in this Chapter are applicable for the following general engineering approaches (according to the "Classic Laminate Theory (CLT)" for CRP). For 3-D finite element analysis the reduction factors have to be defined separately.

Pin seating:

– bearing stress/strain [MPa]:

$$\sigma_b = \frac{F}{t \cdot d} \qquad \varepsilon_b = \frac{\sigma_b}{E}$$

– shear-out stress [2] (for CRP) [MPa]:

$$\tau_{st} = \frac{F}{2 \cdot t \cdot \left(e - \frac{d}{4}\right)} \qquad \varepsilon_{st} = \frac{\tau_{st}}{G}$$

– tensile (hoop) stress [MPa]:

$$\sigma_{hs} = \frac{F}{t \cdot (b - d)} \qquad \varepsilon_{hs} = \frac{\sigma_{hs}}{E}$$

where

t = plate thickness [mm]

d = pin hole diameter [mm]

e = distance from pin centre to edge of component in direction of load [mm]

b = width of component perpendicular to direction of load [mm]

E = mean compression modulus [MPa]

G = mean shear modulus [MPa]

F = design load according to 9.1.1 [N]

This implies, that the construction allows for such simplifications, otherwise stress concentration factors (SCF) have to be incorporated. Index values for SCF are:

– SCF = 3,0 for holes around loaded pins

– SCF = 1,7 for holes in loaded isotropic or quasi-isotropic laminates

Furthermore:

– Bending in bolt-connections must be kept small by choosing an appropriate arrangement.

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2 Shear-out stress has to be considered for bolt-fastenings with an edge distance lower than 2d. In any case, when plate material is not quasi-isotropic.

– Where pins introduce an un-symmetrical loading in a plate due to additional transverse loading (e.g. at forestay attachment), holes shall have a bushing and be clamped. (A clamped laminate is supported by a steel bushing inside a hole and at its cheeks with washers or plates connected to the bushing.)

– An efficient load transfer for local load introductions through bolt-connections in flat CRP-plates can be provided with a quasi-isotropic plate laminate with the following fractions of fibre-directions:

0°: 30 % – 50 %

± 45°: 40 % – 60 %

90°: ≥ 10 %

For minimum elastic off-axis properties, relate also to C.1.3.

9.1.1 Design loads for structural joints, fittings attachments and connections

1,0 × breaking load of the relevant shroud

1,0 × breaking load of the relevant stay

1,0 × release load of halyard tensioners/winches and sheet winches etc.

0,8 × breaking load of running rigging

2,0 × max. working load of running rigging

1,5 × max. vang load (hydraulic device: release load)

Others to be specified in detail.

If more than one design load is relevant, the highest resulting value has to be chosen.

9.1.2 Allowable strains for carbon fibre laminates under design loads

$\varepsilon_{b\ all}$ = 0,25 % allowable bearing strain of carbon laminate with circular holes

$\varepsilon_{bc\ all}$ = 0,35 % allowable bearing strain of clamped carbon laminate with circular holes

$\varepsilon_{ct\ all}$ = 0,25 % allowable compression and tensile strain

$\varepsilon_{is\ all}$ = 0,45 % allowable in-plane shear strain

9.1.3 Applicable reduction factors for carbon fibre laminates under design loads on the basis of appropriate and approved material test data, refer to C.1.3

γ_b = 2,0 against ultimate bearing strain or stress (compressive test)

γ_{bc} = 1,5 against ultimate bearing strain or stress of clamped laminates (compressive test)

γ_{ct} = 2,0 against ultimate compression and tensile strain or stress

γ_s = 2,0 against ultimate in-plane shear strain or stress

9.1.4 Applicable reduction factors for aluminium alloys under design loads

γ_b = 1,1 against ultimate bearing stress

γ_{ct} = 1,1 against ultimate compression and tensile stress

γ_s = 1,1 against ultimate shear stress

For welded components the modified material properties have to be taken into account.

9.2 Local strength of metallic pins and other attachments made of stainless steel or aluminium alloy

γ_y = 1,1 against yield strength under design-loads according to 9.1.1

9.3 Bonded joints

Bonded joints are normally in-plane shear loaded.

γ_{gjb} = 2,0 against ultimate shear strength of adhesive in connection with bolts/rivets

γ_{gj} = 2,5 against ultimate shear strength of adhesive without bolts/rivets

– cleavage is to be avoided

– joints of mast-, boom- or spreader shells shall be located in one of the neutral axis

– structural threads are not allowed in laminates

C. Materials and Fabrication

1. Materials

1.1 CRP in General

A solid laminate lay-up shall have well-balanced mechanical properties, i.e. off-axis fibres evenly distributed, unless special configurations are required in well-founded exceptional cases.

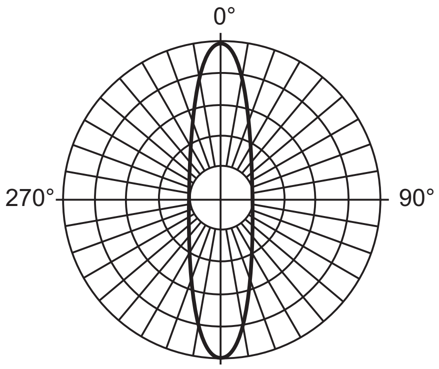
In a laminate a batch of plies with fibres aligned solely in one direction may not exceed a thickness of 1,5 mm or a fibre weight of 1500 g/m^2 respectively. Generally, grouping of 90° plies is to be avoided.

For polymer matrix composites the reinforcement fibre will be the primary load carrying element, because it is stronger and stiffer than the matrix. The mechanism for transferring load throughout the reinforcement is the shearing stress developed in the matrix. Thus, a fibre dominated laminate characteristic is desired wherever possible. A (0°/ ± 45°/ 90°)-lay-up is recommended, a minimum of 10 % of the fibres should be aligned in each of those directions (see also B.9.1).

In any case the transverse young's modulus in compression shall exceed a minimum of 20 % of the value in longitudinal direction. The polar graph of the in-plane young's modulus shall not have major concave areas see Fig. 1.13.

The minimum shear modulus in shell plane shall be not less than 11 % of the young's modulus in compression.

Conditions, where peel stresses occur due to abrupt steps or bonded structures with significantly different stiffnesses are to be avoided.



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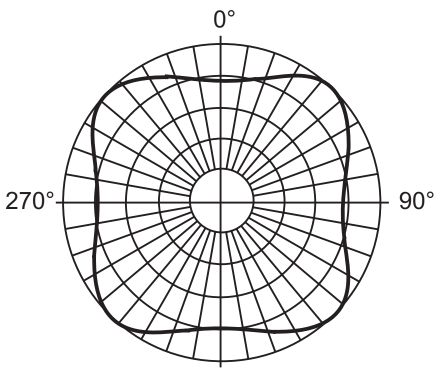

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Fig. 1.13 Polar diagrams

The taper of a laminate, for example reduction of section thickness or a reinforcement patch, has to be carried out according to a proper taper ratio.

When drilling holes in CRP, measures are to be taken to prevent fibres from breaking out of the back face.

1.2 CRP samples

CRP samples of the fabricated tube have to be submitted to GL. Samples can be:

- spar shell ends close behind cut-offs
- pieces from cut-outs, e.g. from:
  - spreaders, tang fittings,
  - halyard slots,
  - others, if available, with designation of their location

Pieces will be stored.

Some of the CRP samples are to be representative of the 0° (longitudinal) direction of the tube with a minimum size of $100 \times 10 \times t$ [mm] for a possible compression test.

1.3 Material Tests (CRP)

Analysis of local details may be performed in a more exact and less conservative way, when reliable test data of the relevant laminate properties are available. However, before applying test data values it must always be considered, whether the test data in question are (really) significant for the particular design problem. Tests have to be carried out according to appropriate standards at an independent, accredited institute. The specimen shall be supplied by the mast-builder and be fabricated under realistic conditions corresponding to the component-construction.

1.4 Design values

For each mechanical property of a laminate a min. number of tests is to be carried out. A statistical average is then to be taken as outlined in the following, to obtain the characteristic value, which will be taken as design value.

A "normal distribution" is assumed for the test values of the mechanical properties. A 5 % fractile for a probability of P = 95 % (confidence interval) is to be applied here. The relevant formula for the characteristic value R_k is:

$$R_k(\alpha, P, s, n) = x - s \cdot \left(u_\alpha + \frac{u_P}{\sqrt{n}} \right)$$

$u_{\alpha/P}$ = $\alpha\,\%/P\,\%$ fractile (percentile value) of a normal distribution for defining a minimum value

= 1,654 for the above condition (α = 5 %, P = 95 %)

x = arithmetic mean value from test results

$$= \frac{\sum_{i=1}^{n} x_i}{n}$$

s = standard deviation

$$= \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - x)^2}$$

x_i = individual test value i of set of n tests

n = number of tests for one mechanical property

Elastic properties for a laminate with off-axis content can be calculated if the properties for the pure unidirectional laminate are known according to the "classic laminate theory". An analogous conclusion for strength properties is unfortunately not possible.

Considering the approaches of B.9.1, it is assumed that the strength properties of a laminate are "fibre-dominated" and the strength properties in the load-related direction are relevant. For a laminate with a minimum of 40 % ± 45° and 10 % 90° layers the ultimate strain in compression or tension is assumed to be governed by the ultimate strain of the 0° plies contained therein. This allows to obtain the ultimate strain values from a 100 % 0° laminate as to represent design values when statistically assured. Further, it will be assumed that the in-plane shear strain is governed by tensile/compression properties of fibres running under ± 45°.

To obtain allowable values, the design values for strength and strain properties have to be combined with the reduction factors (refer to B.9.1.3). Fig. 1.14 illustrates the path and links between load application and load absorption accordingly.

The tests according to Table 1.9 are considered appropriate for the investigation of material properties for CRP.

GL reserves the right to interpret the test data due to different test methods.

1.5 Material Certificates for aluminium alloys

Valid material properties of specific aluminium alloy verified by a "3.1.B. material certificate" according to DIN EN 10204 or similar can be submitted to GL. Otherwise, GL will base the calculations on general minimum properties for the aluminium alloy in question.

1.6 Quality Assurance

An internal quality assurance of the production facility must be guaranteed, e.g. be in compliance with the ISO 9000 series or be suitable for the facilities and comprise inspection of incoming goods, storage of material, responsibilities and the process of fabrication.

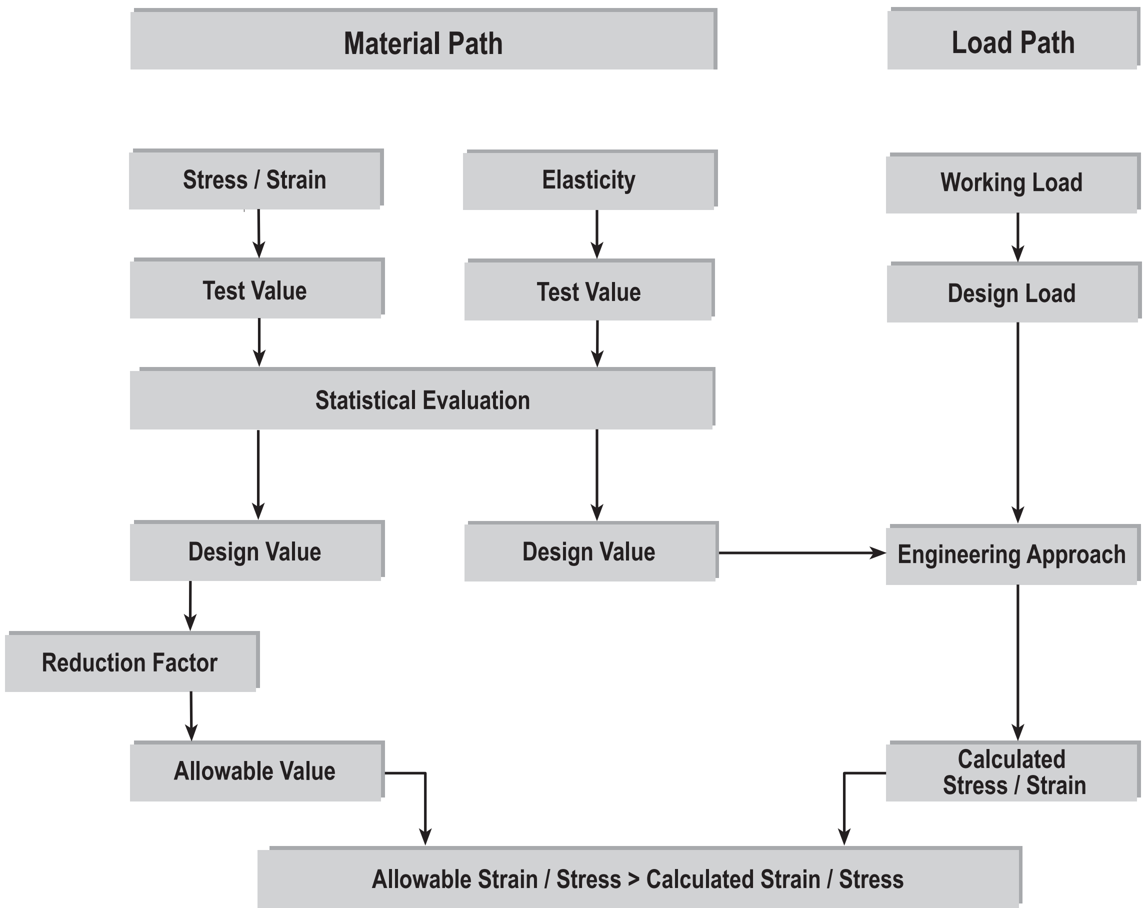

Fig. 1.14 Engineering flow chart

Table 1.9 Material tests

(Tensile strength), tensile modulus, elongation at break	ASTM D3039, SACMA SRM4 or DIN EN ISO 527-4, test specimen III, 5 samples
(Compressive strength), compressive modulus, elongation at break	ASTM D3410, SACMA SRM1 or Draft DIN EN 2850, specimen A1 with free edge of 8 mm, 5 samples
Flexural strength, flexural modulus (if applicable)	ASTM D790, EN 63-ISO 178, 5 samples.
Interlaminate shear strength	ASTM D2344, 5 samples

2. Fabrication

The fabrication of polymer matrix composites shall in general be in compliance with the material suppliers recommendations and/or requirements and GL's Rules for Classification and Construction, II – Materials and Welding, Part 2 – Non-metallic Materials.

D. Miscellaneous

1. Fittings, Equipment

Rigging parts like terminals, turnbuckles, toggles, shackles, eyes, jaws, tip cups are not within the scope of these rules but shall nevertheless be state of the art equipment and/or be chosen from an experienced rig supplier.

Relief valve settings and/or max. pull or max. holding power of non-manual driven devices, that act on standing rigging, are to be adjusted to

– 66 % of the breaking load of the respective stay for rod and wire

– 50 % of the breaking load of the respective stay for aramid rigging

2. Rigging

2.1 Solid rod rigging

Rod rigging shall be equipped with "low fatigue" terminals. Terminals shall be self-aligning under changing lead to avoid bending. The best common fitting for alignment under load is the marine eye combined with a toggle. For transverse rigging, ball-type fittings are also acceptable (stemball fittings), but not so for head stays due to the magnitude of lead change under load.

2.2 Aramid rigging

2.2.1 Soft (flexible) aramid rigging

Soft aramid rigging is generally acceptable for aft longitudinal rigging (backstays, running backstays, checkstays), but not recommended for Category I yachts.

Spliced terminals are not allowed due to the possibility of chafe.

Soft aramid rigging must be proof tested to at least 25 % of the rated strength of the stay prior to installation.

Terminals shall have a sufficient bend and strain relief and transition towards the cable and shall provide a good isolation from salt water, humidity and UV-radiation.

For maintenance recommendations/requirements refer to 3.

2.2.2 Rigid aramid rigging

Rigid (resin impregnated) aramid rigging is generally not to be used for all verticals and the uppermost diagonal. It is also not recommended for Category I yachts.

It can be used for jumper shrouds and diagonals but in case of D1 caution is to be taken due to the proximity to chafe and impact sources.

Rigid aramid rigging should be sized based on its stretch equivalent to metallic (generally "Nitronic-50") rod rigging.

Terminals shall have a sufficient bend and strain relief and transition towards the rod and shall provide a good isolation from salt water, humidity and UV-radiation.

Rigid aramid rigging shall be proof tested to at least 50 % of the rated strength of the shroud prior to installation.

For maintenance recommendations/ requirements refer to 3.

3. Maintenance

Rigging and other highly loaded components of the rig shall be inspected in appropriate intervals, depending on the proportion of usage with non-destructive testing methods, especially at terminals, fittings and ball-heads. Suppliers recommendations have to be considered.

3.1 Rigging and attached fittings

3.1.1 Rod rigging should be replaced, when:

– any kind of crack appears (typically at "cold heads")

– in case of a permanent bent caused by mishandling

A first disassembly and inspection of the rigging should be carried out latest after 2 years (1 year for category III and IV rigs) or 40 000 miles (10 000 miles for Cat III and IV).

3.1.2 Soft aramid rigging

Soft aramid cable must be replaced when the cover is damaged such that the break penetrates to the fibre core.

Rigging should be inspected at least every year (every 1/2 year for category III or IV rigs) or after 10 000 miles (5 000 miles for category III or IV rigs), whichever comes first.

The terminals should be inspected according to suppliers recommendations.

3.1.3 Rigid aramid rigging

Rigid aramid rigging must be replaced when:

– a longitudinal surface crack appears that exceeds three rod diameters in length

– a circumferential crack appears and breaks any fibres

– the rod has drawn down inside the terminal more than one rod diameter while in service

Rigid aramid cables should be inspected at least every year (every 1/2 year for category III or IV rigs) or after 10 000 miles (5 000 miles for category III or IV rigs), whichever comes first.

Rigid aramid cables should be disassembled after the first 2 years (1 year for category III and IV rigs) or 40 000 miles (10 000 miles for category III and IV rigs), whichever comes first. Thereafter, rigid aramid cables should be disassembled after 4 years (2 year for category III and IV rigs) or 40 000 miles (10 000 miles for category III and IV rigs), whichever comes first.

The terminals should be inspected to suppliers recommendation.

4. Coating

All carbon parts that are subjected to direct sunlight shall be protected by a non-transparent, light colour. The thickness shall be sufficient to protect from UV-radiation.

5. Corrosion protection

Metallic parts have to be insulated from carbon fibres by using an adhesive layer or a thin glass fibre ply, which must ensure sufficient protection against conductive connection. The reason is that carbon fibres do not only conduct electrical current, but are also sensitive to cathodic corrosion.

It is generally recommended to wrap carbon-spars in a resin-rich layer of glass woven roving laminate to prevent splintering of carbon fibres in case of damage and to provide a certain protection from local impact.

For spars made of aluminium-alloy, austenitic metals have to be insulated from aluminium alloy components.

6. General recommendations for lightning protection

6.1 An aluminium mast itself is a good conductor with enough cross sectional area to conduct a lightning strike.

6.2 Carbon fibres are not to be used as a conductor.

6.3 For mast heights over 15 m above water line, the protection zone is based on the striking distance of the lightning stroke. Since the lightning stroke may strike any grounded object within the striking distance of the point from which final breakdown to ground occurs, the zone is defined by a circular arc. The radius of the arc is the striking distance (30 m). The arc passes through the top of the mast and is tangent to the water. If more than one mast is used, the zone of protection is defined by arcs to all masts.

The protection zone formed by any configuration of masts or other elevated, conductive and grounded objects can readily by determined graphically. All components inside the protection zone shall be lightning grounded to earth.

6.4 The entire circuit from the top of the mast to the ground shall have a mechanical strength and conductivity not less than that of a 25 mm^2 copper conductor. The path to ground followed by the conductor shall be essentially straight and on the shortest way possible. Corners or sharp edges shall be avoided in conductors.

6.5 For carbon masts it is recommended to protect other cables from (strong) magnetic fields occurring, when passing the conductor through the mast.

6.6 The top of the lightning spike should at least be 300 mm above anything that is sensible in this context (structure, antenna, instruments), see also definition of "protection zone" in 6.3.

6.7 The lightning spike should have a metallic diameter of not less than 8 mm.

Also refer to ISO 10134 and/or GL Rules for Pleasure Craft Annex E.

7. Inclining test

An inclining test about the initial stability shall be performed to confirm the assumptions of calculations.

8. Stepping and rigging of masts

The stepping and rigging of a mast has to be performed by experts according to the designers/manufacturers specifications.

9. Visual pre-delivery inspection

It is strongly recommended to carry out a shake-down cruise of at least 7 days offshore. Wind speeds of at least 25 – 30 knots have to be experienced over a period of at least 24 hours.

A visual inspection of the rig will in any case be carried out prior to delivery.

E. Certificate

A certificate will be issued, once the design has successfully passed the approval and a visual inspection has shown satisfactory results. Though the approval will render invalid, when the construction does not comply with the drawings and/or when modifications in design or construction are being made, without informing GL. The repair of structural components are to be agreed with GL for maintaining the validity of the certificate.