STANDARD

DNVGL-ST-0490 Edition October 2016

TP52 racing yachts

DNV GL AS

FOREWORD

DNV GL standards contain requirements, principles and acceptance criteria for objects, personnel, organisations and/or operations.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

This is a new document.

CONTENTS

SECTION 1 GENERAL REQUIREMENTS

1.1 Application

1.1.1

This standard applies to sailing yachts which shall be built in accordance with the rules for TP52 class racing yachts, under the condition that the yacht is at all times employed exclusively under the conditions for which she has been designed, constructed and approved for and that she is handled correctly in terms of good seamanship.

1.1.2

Should other rules apply to the certification of the yacht (e.g. class rules, relevant ISO standards, *World Sailing Offshore Special Regulations*) and definitions or requirements contradict with the ones in this standard, clarification shall be sought by the designer, boat yard, owner et al.

1.1.3

Essential assessments for structural integrity of hull structures include the review of strength and stiffness of primary hull structural members based on reviewing relevant design drawings and documentation.

1.1.4

Implications on structural integrity based on actual construction performance, skills and methods will not be considered. It will be presumed that design and construction are of best practice.

1.1.5

Material manufacturer instructions shall be followed but are in general not subject on plan review assessments.

1.1.6 Operating category

The scantlings of hull primary structural members apply to operating in open seas without restriction.

1.2 Scope

1.2.1 General

1.2.1.1 The standard considers primarily structural integrity of yacht's hull including structural components listed in [1.3.3.2]. Any note in this standard addressing issues other than structural integrity shall be considered as recommendation or guidance to designer, builder, owner, et al.

1.2.1.2 The requirements of this standard does not substitute the independent judgment of professional designers. This is particularly valid for those aspects not addressed in these standards and for which the designers are solely responsible.

1.2.2 Scope and depth of plan approval

1.2.2.1 The yacht’s structure is being exposed to quasi static and quasi dynamic sea loads and/or other operational loads as per standard’s definition.

1.2.2.2 Indicative list of typical components included in plan review:

— hull: hull shell, deck shell, primary girders and stiffeners, frames, ring frames, bulkheads, decks, soles, stern and transom, joining of components, global and local reinforcements.
— rudder incl. shaft, shaft bearings and their structural integration.
— reel: keel arrangement, keel bulb, keel fin and its structural attachment to hull; hull structure in way of keel attachment
— structural attachments of primary structural members as listed above

1.3 Certification

1.3.1 General

1.3.1.1 The relation between the customer and DNV GL is regulated in an agreement signed by both parties. The agreement specifies the scope of the service, the fee, terms of payment and legal obligations.

1.3.1.2 The certification service is performed on the basic assumption that all parties involved (designer, builder/yard, manufacturer, design-owner, sub-contractor, owner, etc.) fulfil their individual obligations. The certification service is not performed in substitution of other parties' role or obligations. Nothing contained in DNV GL services, certificate, report or document issued in connection with or pursuant to these requirements, shall relieve any designer, engineer, builder, manufacturer, yard, seller, owner, operator or other parties from any obligations or consequences of default whatsoever. In particular, compliance with the requirements does not imply acceptance or commissioning of a yacht. This is the exclusive responsibility of the owner.

1.3.2 Certification - procedure

1.3.2.1 General

1.3.2.1.1 Application for certification shall be sent to the undersigned DNV GL office and include:

— name and address of the applicant
— technical documentation.

1.3.2.1.2 The applicant has to be authorised by the owner of the design to act on his behalf.

1.3.2.1.3 If the applicant subcontract design, the applicant remains responsible for the execution of conformity assessment for all technical documentation and sub-supplies.

1.3.2.1.4 Any subcontracting will be subject to separate agreement, handling and approval.

1.3.2.1.5 DNV GL decides the extent of examinations.

1.3.3 Documentation requirements

1.3.3.1 General requirements

1.3.3.1.1 All documents submitted to DNV GL shall be in English language.

1.3.3.1.2 The drawings shall contain all data necessary for assessment and approval. Where deemed necessary, calculations and descriptions of the yacht's elements are to be submitted. Any non-standard symbols used shall be explained in a key list. All documents shall show the project name, drawing number and revision number.

1.3.3.1.3 Submitted documentation about performed calculations shall contain all necessary information concerning reference documents, literature and other sources. The calculations shall be compiled in a way which allows identifying and checking all steps. Handwritten, easily readable documents are acceptable. Where appropriate, results of calculations shall be presented in graphic form. A written conclusion shall be provided.

1.3.3.1.4 DNV GL reserves the right to inquire additional documentation if the submitted is insufficient for an assessment of the yacht or essential parts thereof. This may especially be the case for components related to new developments and/or which have not been tested on board to a sufficient extent.

1.3.3.2 Submission of documents

1.3.3.2.1 Upon request the list of required documents to be submitted will be provided by DNV GL.

1.3.3.2.2 Drawings shall be submitted in pdf format in general. The documents to be submitted for plan approval are listed below. For the purpose of submission, DNV GL provides a digital platform called MYDNVGL.

1.3.3.2.3 General information

— list of submitted drawings (title, dwg.no., date of latest revision)
— structural general arrangement, deck plan
— technical specification (main dimensions, displacement, etc.) – “DNV GL_WORLD SAILING_Plan_Review_Data.XLS”
— material specifications – “DNV GL_WORLD SAILING_Plan_Review_Data.XLS”

1.3.3.2.4 Structural components of the hull

— structural members of the hull shown in side view, plan view and cross sections (bulkheads, frames, floors, etc.)
— hull and deck
— bonding of structural components
— hull to deck joint

1.3.3.2.5 Keel design

— keel geometry, weight and centre of gravity
— section of the keel root and positioning of keel bolts or accordingly
— position of root and bolts relative to the keel floors
— area of keel-hull connection, pos. include flange
— material specification of keel, -bolts and diameter
— anchoring of bolts in the keel
— typical keel foil sections
— specification of welding (if applicable)

1.3.3.2.6 Rudder design

- — geometry of rudder
- — blade sections
- — dimensions of the rudder stock specification
- — rudder stock tube and weight-carrying bearing
- — position of rudder bearings
- — specification of rudder bearings (dimensions, maximum working loads)
- — bearing seats
- — integration of stock in rudder body
- — laminate specification of the rudder blade

1.3.4 Certificates

1.3.4.1 General

1.3.4.1.1 The type of certificate to be issued by DNV GL will be:

- — Product certificate

1.3.4.1.2 The certificates shall contain the following information, as applicable:

- — the name and address of the builder (yard, manufacturer)
- — the identification of the product/craft type designation and reference to owner of the design
- — reference to the standard and regulations applied
- — specification of exemptions or equivalent standards
- — date of issue and signatures.

1.4 Definitions

1.4.1 Principal dimensions

All principle dimensions are measured at displacement D.

1.4.2 Scantling length L

In accordance with the TP class rules the scantling length is L = 15.85 m.

1.4.3 Beam B_{WL}

The beam B_{WL} [m] is the maximum breadth of the craft measured from one shell outer edge to the other at the waterline WL, as defined in Figure 1-1.

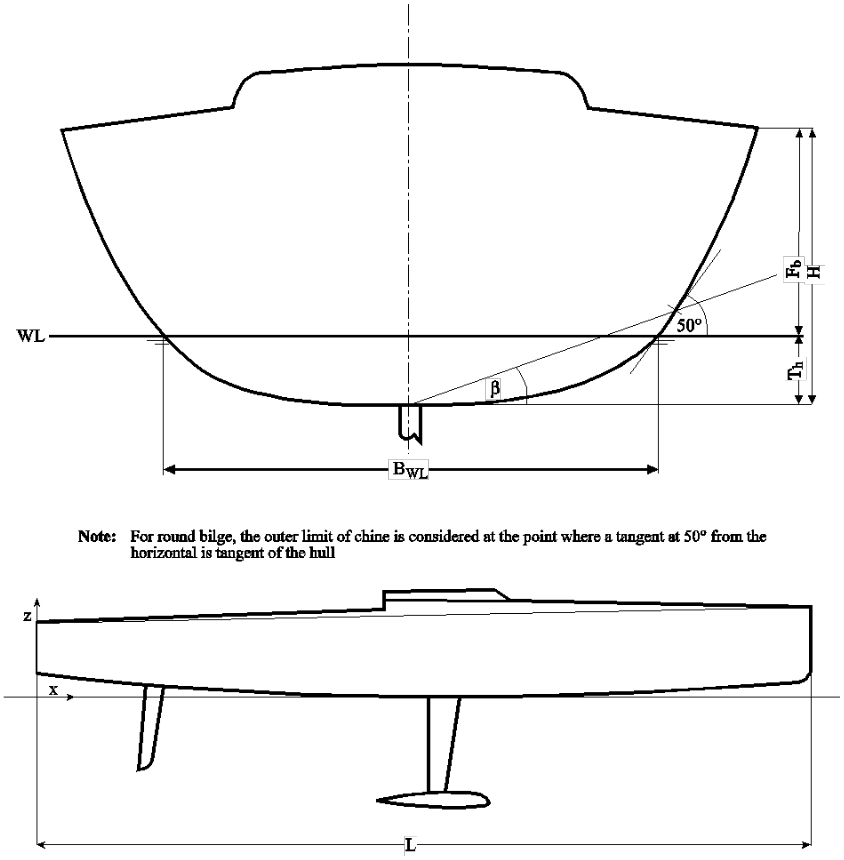

Figure 1-1 Dimensions and coordinate system

1.4.4 Depth H

The depth H [m] is the vertical distance between the hull bottom and the sheer point measured at the side of the craft halfway along L_{WL}, as in Figure 1-1. The sheer point is the point between hull and deck where a tangent at 45 degrees can be rested.

1.4.5 Draught T

The draught T [m] is the vertical distance between the waterline WL of the craft in the ready to operate condition and the bottom edge of the keel.

1.4.6 Freeboard F_b

The freeboard is the minimum distance between the waterline and the upper edge of the shearline or an opening in the hull without a watertight closure.

1.4.7 Speed v

For the structural design of the hull a design speed of

$$v = 3.0 \cdot \sqrt{L} = 12 \text{ kn}$$

shall be adopted.

For the calculation of the rudder forces a design speed of

$$v_0 = 3.5 \cdot \sqrt{L} = 14 \text{ kn}$$

shall be adopted.

1.4.8 Displacement D

The displacement D [t] is the weight of the craft in the fully loaded ready- for- use condition as defined in ISO 8666.

1.4.9 Hull

1.4.9.1 General

The hull of a vessel in the terms of this standard is the floatation body up to a 45° tangent on the deck sheer line.

1.4.9.2 Bottom areas

The bottom area of the hull is defined up to 200 mm above waterline (WL).

1.4.9.3 Side areas

The extent of the side pressure area, which includes the transom, is part of the hull not considered as belonging to the bottom area.

1.4.9.4 Deck

Deck areas are parts of the deck exposed to weather and where persons are liable to walk. Cockpit bottom, -side and –top and coachroof side areas are included.

1.4.10 Coordinate system

For the description of the yacht's geometry the fixed, right-handed coordinate system 0, x, y, z as defined on Figure 1-1 is introduced. The origin of the system is situated at the aft end of L, at centreline and on the moulded baseline on the yachts hull. The x-axis points in longitudinal direction of the yacht positive forward, the y-axis positive to port and the z-axis positive upwards. Angular motions are considered positive in a clockwise direction about three axes.

1.4.11 Computational software

1.4.11.1 General

In order to increase the flexibility in the structural design of yachts, DNV GL also accepts direct calculations using computational software.

Note:

The aim of such analyses should be the proof of equivalence of a design with the rule requirements.

---e-n-d---o-f---n-o-t-e---

1.4.11.2 General programmes

The choice of computational software according to the "State of the Art" is free. The programs may be checked by DNV GL through comparative calculations with predefined test examples. A generally valid approval for a computer program is, however, not given by DNV GL. DNV GL reserve the right to refuse to use computational software for some applications.

For such calculations, the structural model, boundary conditions, load cases and applicable material allowable (strength, strain) shall be agreed upon with DNV GL. Calculation documents shall be submitted including input and output. During the examination it may prove necessary that DNV GL perform independent comparative calculations.

SECTION 2 DESIGN LOADS

2.1 General

In the following design pressure equation will be specified. Related allowable stresses and strains are given in Sec.3 [3.3.9].

2.2 Hull design pressures

2.2.1 Bottom design pressure P_b

The bottom design pressure P_b shall be the greater of the bottom impact pressure P_{b1} or the bottom sea pressure for displacement mode P_{b2}.

2.2.2 Bottom impact pressure P_{b1} [kPa]

$$P_{b1} = \frac{100 \cdot D}{L \cdot B_{WL}} \cdot \left(1 + n_{cg}\right) \cdot k_L \cdot k_{ar}$$

2.2.2.1 Dynamic load factor n_{cg} in units of [g]

$$n_{cg} = 0.00013 \cdot \left(\frac{L}{10 \cdot B_{WL}} + 0.084\right) \cdot \left(50 - \beta\right) \cdot \frac{v^2 \cdot B_{WL}^2}{D}$$

β = deadrise angle at 0.4 L_{WL} from the aft end of WL to be taken between 10° and 30° (acc. Figure 1-1)

n_{cg} = shall not exceed a value of 4.

2.2.2.2 Longitudinal distribution factor k_L

$$k_L = 0.13 \left[1.4 \cdot x_L \cdot \left(10 - \frac{v}{\sqrt{L}}\right) + 0.706 \cdot \frac{v}{\sqrt{L}} + 0.64\right]$$

$$x_L = \frac{x}{L}$$

is the position ratio where x [m] is the distance from the origin.

$$k_{L,min} = 0.13 \cdot \left(0.35 \cdot \frac{v}{\sqrt{L}} + 4.14\right)$$

$$k_{L,max} = 1.0$$

2.2.2.3 Design area reduction factor k_{ar}

$$k_{ar} = 0.673 - 0.52 \cdot \frac{u^{0.75} - 1.7}{u^{0.75} + 1.7}$$

$$u = 100 \cdot \frac{A_d}{A_r}$$

$k_{ar,\,min} = 0.4$

2.2.2.4 Reference area A_r

$$A_r = 0.45 \cdot L \cdot B_{WL} \quad \text{in } [m^2]$$

2.2.2.5 Design area A_d [m^2]

- for plating: the panel panel is not to be taken greater than 2.5 times b^2 where b is the short panel span
- for stiffeners: the stiffener length ℓ times the stiffener spacing not to be taken less than 0.33 times ℓ^2

2.2.3 Bottom sea pressure Pb2 [kPa]

$$P_{b2} = 11.76 \cdot \left(3 \cdot T_c + 0.23 \cdot L\right) \cdot k_{ar} \cdot k_L$$

$$P_{b2,\,min} = 10 \cdot H$$

H = see [1.3]

k_L, k_{ar} = see [2.2.2], [2.2.3]

T_c = hull draught [m] not to be taken less than

$$T_{c\,min} = 0.062 \cdot L - 0.26 = 0.723$$

2.2.4 Side design pressure for sailing craft P_{sS} [kPa]

$$P_{sS} = 7.14 \cdot (2 \cdot T_c + 0.23 \cdot L) \cdot k_{ar} \cdot k_L$$

$$P_{sS,min} = 5 \cdot H$$

2.2.5 Deck design pressure P_d [kPa]

$$P_d = 0.11 \cdot L + 5.35$$

2.2.6 Design pressure for watertight bulkheads p_{bh} [kPa]

$$p_{bh} = 10 \cdot h_z$$

h_z = vertical distance from centre of bulkhead plate or stiffener to the top of the bulkhead [m]

2.3 Design loads for keel and keel attachments

2.3.1 General

The structure of the ballast keel and also the yacht's bottom and floor structure in way of the keel attachment shall be able to withstand the structural loadings described below. All relevant structural components of such an assembly shall be assessed, at different locations, as applicable (e.g. keel fin, floors, etc.).

2.3.2 Design loads

The following cases may be assessed separately for the purpose of deriving scantling requirements

2.3.2.1 Transversal keel load, LC1

For the determination of structural response on keel design forces F_y, relevant values of m_k, occurring at pertinent the center of gravity (CoG), shall be taken to assess structural aspects at different locations, e.g. keel root, half span of fin or bulb attachment.

$F_y = 1.2 \cdot m_k \cdot g$ [kN]

m_k = mass of the keel [t]
g = gravitational acceleration = 9.81 m/s^2

2.3.2.2 Vertical keel load, LC2

For the determination of structural response, the vertical design force is acting upwards on the bulb bottom, in line with total keel CoG.

$F_z = 1.1 \cdot g \cdot (D - m_k)$ [kN]

2.3.2.3 Grounding keel load, LC3

For the determination of structural response, the design forces are applied to the foremost tip of the keel bulb.

F_x = $1.32 \cdot g \cdot (D - m_k)$ [kN]
F_y = $0.45 \cdot F_z$

2.4 Rudder design loads

2.4.1 General

This paragraph is typically applicable for high aspect ratio spade rudders mounted behind the keel, with its upper edge close to the hull.

It is assumed that the main dimensioning force is the resultant hydrodynamic lift force occurring at the design speed. Still, a rudder and its associated components and other affected structures have to cope with a minor drag force. For typical rudder shapes and arrangements the following methodology covers moderate astern speed.

2.4.2 Design loads

2.4.2.1 Rudder hydrodynamic side force

The rudder force to be used for determining the component scantlings shall be calculated in accordance with the following equation:

$$C_R = 174 \cdot v_0^2 \cdot A \quad [N]$$

A = total surface area of rudder [m^2]

v_0 = see [1.3.7]

L = in accordance with [1.3.2] [m]

2.4.2.2 Torsional moment

The torsional moment to be transmitted by the rudder and the shaft shall be calculated in accordance with the following equation:

$$Q_R = C_R \cdot r \quad [Nm]$$

r = $x_c - f$[m], if the axis of rotation lies within the rudder

$x_c + f$[m] , if the axis of rotation is forward of the rudder

x_c, f, r_{min} [m] dependent on the type of rudder as in Figure 2-1.

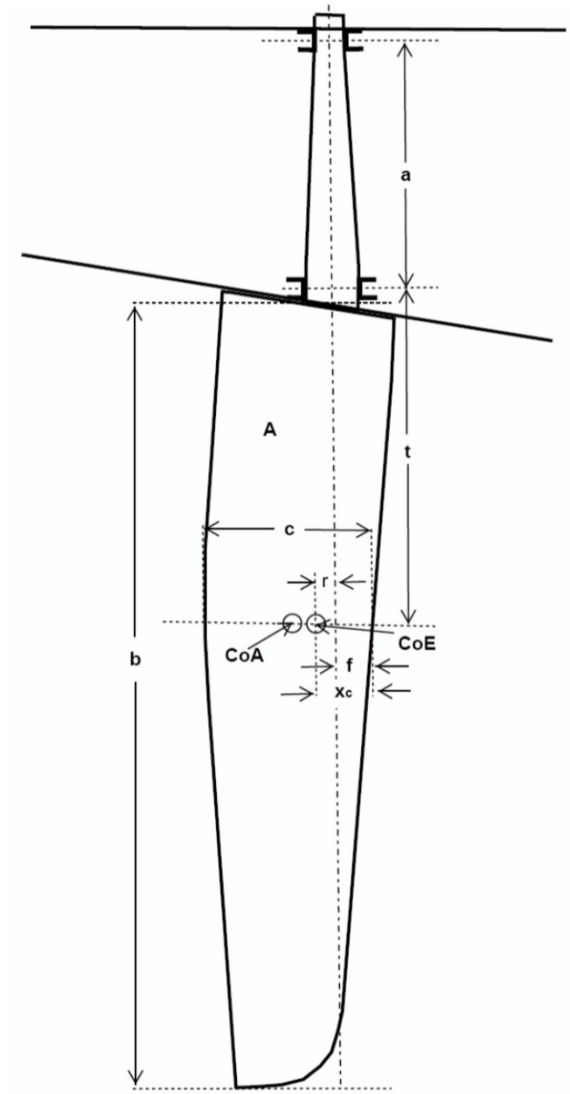

Figure 2-1

A	=	geometric lateral area of the rudder blade
CoA	=	geometric centre of rudder blade
CoE	=	hydrodynamic centre of effort
b	=	mean span of the rudder blade
c	=	averaged profile depth at CoA, CoE c = A/b
r	=	distance between CoE and rudder shaft axis $r = x_c - f$ $r_{min} = 0.1 \cdot c$ $x_c = 0.3 \cdot c$ see Figure 2-1
f	=	lead of trailing edge fwd. of rudder axis

t = distance between CoE and centre of lower bearing

a = distance between bearing centres

2.4.2.3 Rudder bearings

The rudder force C_R shall be distributed between the individual bearings according to the vertical position of the rudder's geometric centre of effort which can be assumed at the same height as the geometrical centre of the blade.

The forces on the bearings shall be calculated as follows:

Bearings of spade rudders:

Bearing force $B_1 = B_2 + C_R \quad [N]$

Bearing force $B_2 = \frac{C_R \cdot t}{a} \quad [N]$

SECTION 3 DESIGN AND SCANTLING DETERMINATION

3.1 General for composite structures

3.1.1 Scope

The following specifies requirements for design and construction of hulls for sailing yachts constructed from composite materials. The term composite refers to fiber reinforced plastic (FRP) materials of single skin type or to FRP skins in conjunction with lightweight core materials, i.e. sandwich types.

3.1.2 Documentation requirements

For all structural composite materials used, the following descriptions shall be provided.

3.1.3 Fiber and resin materials

— resin system, specific gravity

Cured ply properties for:

— fibre areal weight
— fibre orientation
— thickness of the individual layers
— defined direction of mechanical properties
— longitudinal and transverse stiffness, in-plane shear stiffness
— longitudinal, transverse ultimate tensile and compressive strength, in-plane ultimate shear strength.

3.1.4 Core materials

— consolidation method and fiber volume fraction
— type, manufacturer
— nominal density
— thickness
— ultimate shear strength
— compressive modulus
— shear modulus.

3.1.5 Laminates

For each structural component, the documentation must contain on indication of laminate layup including listing of individual layers and their orientation vs. defined coordinate system, geometrical data about location, longitudinal and transverse span of panel, curvature of panel.

3.2 Principles for composite structural design

3.2.1 General structural arrangement

3.2.1.1 The hull structural arrangement shall consist of an effective strengthening system of bulkheads, web frames, longitudinal girders, etc. as well as transverse and/or longitudinal frames or stiffeners. Longitudinal stiffeners shall be supported by transverse web frames or transverse bulkheads. Transverse frames shall be supported by longitudinal girders or other longitudinal structural members.

Where bulkheads, bunks, shelves, or other structurally effective interior components are laminated to the hull to provide structural support, they are generally to be bonded by laminate angles on both sides.

3.2.1.2 Care shall be taken to ensure structural continuity and to avoid sharp corners and abrupt changes in section and shape.

Where frames, beams and stiffeners are intercoastal at an intersecting member, the connections shall provide continuity of strength.

3.2.2 Constructional details

3.2.2.1 L-flange girders/ stiffeners/ frames shall be supported in sharp radii or knuckles by wedges or other sufficiently designed arrangements, as applicable.

3.3 Scantlings

3.3.1 General

The subsequent requirements are applicable under the following conditions:

Loads and design pressures are of maximum service loads character. Possible reductions on particularly rare loading scenarios have not been implemented and yet should be handled case by case.

The following methodology typically applies to orthogonal structured components with a clear hierarchy of structural members. Where this condition is not fulfilled, more comprehensive investigations shall be applied, e.g. grillage analysis.

The orthogonal structured components are assumed to have constant structural and material properties along their length, respectively. If this is not the case, the locations of highest bending moment and shear force can vary from the general assumptions within this section and thus need to be treated specifically (e.g. stiffener or girder with varying height or laminate).

3.3.2 Given frame by rules for TP52 class

The specific TP52 structural requirements are given in the latest rules of the TP52 class.

3.3.3 Composite structures

3.3.3.1 Elasto-mechanical properties of laminated structures

3.3.3.1.1 Nomenclature

ψ = mass content of reinforcing material in a laminate
φ = volume content of reinforcement material in a laminate
E_{11} = Young's modulus of a single ply with unidirectional fibres, parallel to fibres
E_{22} = Young's modulus of a single ply with unidirectional fibres, perpendicular to fibres
ν_{12}, ν_{21} = Poisson's ratios of a single ply
G_{12} = shear modulus of a single ply
ρ_f = specific gravity of fibre material
ρ_m = specific gravity of matrix material
E_{fL} = Young's modulus of fibre in fibre direction
E_{fT} = Young's modulus of fibre transverse to fibre direction
E_m = Young's modulus of matrix

ν_{f12} = Poisson's ratio of fibre
ν_m = Poisson's ratio of resin
G_m = shear modulus of the matrix
G_f = shear modulus of the fibre
E_x = Young's modulus of a ply, multiply or laminate in x-direction of global laminate co-ordinate system
E_y = Young's modulus of a ply, multiply or laminate in y-direction of global laminate co-ordinate system
G_{xy} = shear modulus of a ply, multiply or laminate in xy-direction of global laminate co-ordinate system
Θ = angle of inclination/transformation from local ply coordinate system (1, 2 coordinates) to global laminate coordinate system (x, y coordinates), see Figure 3-1
laminate = is a general expression for a structural unity, a composition of structural fibres, laid down in a polymer matrix. A laminate may contain a sandwich core or other constituents for achieving certain mechanical purposes.

3.3.3.1.2 layer types:

ply = In the definition of these rules, a ply is one laminated layer containing fibre reinforcements aligned in one direction only (unidirectional) or one layer of isotropic or quasi-isotropic material (chopped strand mat (CSM)

multiply = A multiply is consisting of a limited number of plies of different alignments (e.g. laminated fabrics, such as bi-axial, tri-axial, quad-axial, in woven or stiched arrangement, or as pre-preg).

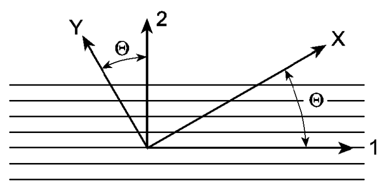

Figure 3-1 Local single ply and global laminate coordinate systems

3.3.3.2 Basic single ply analysis

3.3.3.2.1 Fibre content by volume

The fibre volume fraction of a laminate is determined by the equation:

$$\varphi = \frac{\psi}{\psi + (1-\psi)\cdot\frac{\rho_f}{\rho_m}}$$

The thickness $t_{i,ply}$ of a single ply is then derived as:

$$t_{i,ply} = m_{fi}\cdot\left(\frac{1}{\rho_f} + \frac{1-\psi_i}{\psi_i\cdot\rho_m}\right)$$

m_{fi} = single ply areal weight of fibre reinforcements

ψ_i = fibre mass fraction of single ply

3.3.3.2.2 Basic ply stiffness properties

A single unidirectional laminated ply consists of long fibres, oriented in one direction, embedded in a polymeric matrix. Typical fibre materials are E-glass, aramid or carbon. Representative material properties of fibre and matrix materials can be found in Table 3-1.

The following values are derived for plies containing unidirectional fibres. From those, the properties of multiaxially aligned laminated plies may be derived. CSM's are considered separately in [3.3.3.2.3].

Longitudinal Young´s modulus:

$$E_{11} = \varphi \cdot E_{fL} + (1-\varphi) \cdot E_m$$

Transverse Young's modulus:

$$E_{22} = \frac{E_m}{1-{\nu_m}^2} \cdot \frac{1+0.85 \cdot \varphi^2}{(1-\varphi)^{1.25} + \varphi \cdot \dfrac{E_m}{E_{fT} \cdot (1-{\nu_m}^2)}}$$

Poisson's ratios:

$$\nu_{12} = \varphi \cdot \nu_{f12} + (1-\varphi) \cdot \nu_m$$

$$\nu_{21} = \nu_{12} \cdot \frac{E_{22}}{E_{11}}$$

Shear modulus:

$$G_{12} = G_m \cdot \frac{1+0.8 \cdot \varphi^{0.8}}{(1-\varphi)^{1.25} + \dfrac{G_m}{G_{f12}} \cdot \varphi}$$

$$G_m = \frac{E_m}{2 \cdot (1+\nu_m)}$$

3.3.3.2.3 Stiffness properties of chopped strand mat

The Young's modulus of a CSM laminate can be calculated as:

$$E_{CSM} = \frac{3}{8} \cdot E_{11} + \frac{5}{8} \cdot E_{22}$$

$$G_{CSM} = \frac{E_{CSM}}{2 \cdot (1+\nu_{CSM})}$$

with E_{11} and E_{22} determined like for a basic single unidirectional layer with fibre volume content appropriate for CSM.

Table 3-1 Constituent materials properties

			Fibres				*Matrices*	
			E-Glass	*Aramid*	*HS Carbon*	*HM Carbon [1)]*	*Polyester*	*Epoxy*
Specific gravity		*[g/cm^3]*	2.54	1.44	1.74	1.81	1.2	1.2
Young's Modulus	parallel to fibres	[MPa]	73000	124000	230000	392000	3000	3600
	perpendicular to fibres	[MPa]	73000	6900	28000	15000		
Shear Modulus		[MPa]	30000	2800	50000	28600	1140	1330
Poisson's ratio		–	0.18	0.36	0.23	0.20	0.316	0.35
1) Consider max Young's modulus given in 3.3.3.2								

3.3.3.3 Single ply stiffness

The representative stiffness values for a single ply that is part of a multiply fabric or a laminate is derived in three steps. Firstly the stiffness matrix Q is computed for each ply from its engineering constants in the local coordinate system (ref. [3.3.3.1.2]). In a second step, the stiffness matrix Q is transformed to the global coordinate system, resulting in the transformed stiffness matrix Q' (ref. [3.3.3.3.2]). From this, the engineering constants of each ply in the global laminate coordinate system are determined in a third step (see [3.3.3.5]).

3.3.3.3.1 Stiffness matrix of single ply in local coordinate system

The components of the stiffness matrix are determined for an orthotropic ply, which is part of a non-woven or woven fabric and are calculated as follows:

$$Q11 = \frac{E_{11}}{(1 - \nu_{12} \cdot \nu_{21})}$$

$$Q12 = \frac{\nu_{21} \cdot E_{11}}{(1 - \nu_{12} \cdot \nu_{21})}$$

$$Q22 = \frac{E_{22}}{(1 - \nu_{12} \cdot \nu_{21})}$$

$$Q33 = G_{12} \cdot a$$

$$Q21 = Q12$$

Q = Stiffness matrix of orthotropic layer in local ply coordinate system
a = 1.0, for a non-woven fabric
a = 1.2, for satin (1×8 or 1×6) weave style fabrics
a = 1.5, for twill (2×2, 3×1, 4×4) weave style fabrics
a = 2.0, for plain (1×1) weave style fabrics

Stiffness matrix components Q for chopped strand mat (CSM) shall be derived using the above equations, too, where:

$$E_{11} = E_{22} = ECSM$$

$$\nu_{12} = \nu_{21} = 0.28$$

$$G_{12} = GCSM$$

3.3.3.3.2 Angle transformation for single unidirectional ply stiffness's to global coordinate system

The following equation are used to transform elasto-mechanical properties found in [3.3.4.1] for a unidirectional laminated ply in the local 1, 2 coordinate system to the global x, y coordinate system by an in-plane polar transformation of angle "Θ".

$$Q11' = Q11 \cdot \cos^4\Theta + 2 \cdot (Q12 + 2 \cdot Q33) \cdot \sin^2\Theta \cdot \cos^2\Theta + Q22 \cdot \sin^4\Theta$$

$$Q22' = Q11 \cdot \sin^4\Theta + 2 \cdot (Q12 + 2 \cdot Q33) \cdot \sin^2\Theta \cdot \cos^2\Theta + Q22 \cdot \cos^4\Theta$$

$$Q23' = Q32' = (Q22 - Q12 - 2 \cdot Q33) \cdot \cos^3\Theta \cdot \sin\Theta - (Q11 - Q12 - 2 \cdot Q33) \cos\Theta \cdot \sin^3\Theta$$

$$Q13' = Q31' = (Q22 - Q12 - 2 \cdot Q33) \cdot \cos\Theta \cdot \sin^3\Theta - (Q11 - Q12 - 2 \cdot Q33) \cos^3\Theta \cdot \sin\Theta$$

$$Q12' = (Q11 + Q22 - 4 \cdot Q33) \cdot \sin^2\Theta \cdot \cos^2\Theta + Q12 \cdot (\sin^4\Theta + \cos^4\Theta)$$

$$Q33' = (Q11 + Q22 - 2 \cdot Q12 - 2 \cdot Q33) \cdot \sin^2\Theta \cdot \cos^2\Theta + Q33 \cdot (\sin^4\Theta + \cos^4\Theta)$$

$$Q21' = Q12'$$

Θ = Angle of transformation
Q' = Transformed stiffness matrix of orthotropic layer in global coordinate system

3.3.3.4 Stiffness properties of a single or multiply layer

The multiply is a layer, which is treated as laminate with a distinct number of plies (e.g. woven, stitched or pre-pregged; bi-axial, tri-axial or quad-axial arrangement) and is considered to be one layer of fabric used to build up a laminate.

The stiffness properties of this single or multiply layer will be determined by Classical Laminate Theory with the exception that coupling effects causing out-of plane deformations are restrained.

Thus, the bending extension coupling effects of the single or multiply will be neglected here by forcing the coupling matrix "B" to be zero. This simulates the multiply to be symmetrical.

Following the classical laminate theory the ABD_L matrix is the stiffness matrix of the multiply (Index "L" for "layer") and will lead to the engineering constants of the multiply.

The individual matrices are calculated as follows:

Extension matrix A_L:

$$A11_L = \sum_{i=1}^{n} Q11'_i \cdot t_i$$

$$A12_L = A21 = \sum_{i=1}^{n} Q12'_i \cdot t_i$$

$$A13_L = A31 = \sum_{i=1}^{n} Q13'_i \cdot t_i$$

$$A22_L = \sum_{i=1}^{n} Q22'_i \cdot t_i$$

$$A23_L = A32 = \sum_{i=1}^{n} Q23'_i \cdot t_i$$

$$A33_L = \sum_{i=1}^{n} Q33'_i \cdot t_i$$

Bending extension matrix B_L:

All forced to be zero:

$$B11_L = B12_L = B13_L = B21_L = B22_L = B23_L = B31_L = B32_L = B33_L = 0$$

Bending matrix D:

$$D11_L = \frac{1}{3}\sum_{i=1}^{n} Q11'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D12_L = D21 = \frac{1}{3}\sum_{i=1}^{n} Q12'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D13_L = D31 = \frac{1}{3}\sum_{i=1}^{n} Q13'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D22_L = \frac{1}{3}\sum_{i=1}^{n} Q22'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D23_L = D32 = \frac{1}{3}\sum_{i=1}^{n} Q23'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D33_L = \frac{1}{3}\sum_{i=1}^{n} Q33'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

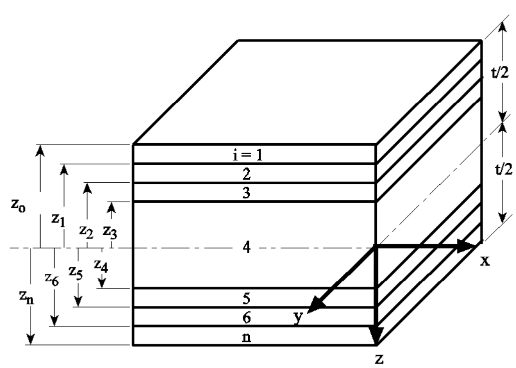

Figure 3-2 Ply definitions

Resulting in the ABD_L matrix:

$$\begin{bmatrix} A11_L & A12_L & A13_L & 0 & 0 & 0 \\ A21_L & A22_L & A23_L & 0 & 0 & 0 \\ A31_L & A32_L & A33_L & 0 & 0 & 0 \\ 0 & 0 & 0 & D11_L & D12_L & D13_L \\ 0 & 0 & 0 & D21_L & D22_L & D23_L \\ 0 & 0 & 0 & D31_L & D32_L & D33_L \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}_L$$

and the inverse ABD*L* matrix

$$\begin{bmatrix} a11_L & a12_L & a13_L & 0 & 0 & 0 \\ a21_L & a22_L & a23_L & 0 & 0 & 0 \\ a31_L & a32_L & a33_L & 0 & 0 & 0 \\ 0 & 0 & 0 & d11_L & d12_L & d13_L \\ 0 & 0 & 0 & d21_L & d22_L & d23_L \\ 0 & 0 & 0 & d31_L & d32_L & d33_L \end{bmatrix} = \begin{bmatrix} a & b \\ b & d \end{bmatrix}_L = \begin{bmatrix} A & B \\ B & D \end{bmatrix}_L^{-1}$$

The engineering constants for the multiply layer are:

$$E_x = \frac{1}{t \cdot a11};$$

$$E_y = \frac{1}{t \cdot a22};$$

$$G_{xy} = \frac{1}{t \cdot a33};$$

$$\nu_{xy} = -\frac{a_{12}}{a_{11}}$$

The following layer stiffness values will be used for buckling analysis in [3.3.7.2]:

$$Q11'_L = \frac{A11_L}{t_L}$$

$$Q12'_L = \frac{A12_L}{t_L}$$

$$Q22'_L = \frac{A22_L}{t_L}$$

$$Q33'_L = \frac{A33_L}{t_L}$$

$$Q21'_L = Q'12_L$$

t_L = thickness of single or multiply layer

3.3.3.5 Laminate stiffness

3.3.3.5.1 Single skin laminates

A single skin laminate is consisting of a total of n laminated layers, where the index i stands for a particular layer of this compound. The following is also valid for determining the properties of sandwich skins each: The following areas shall be of single skin construction

— keel root area
— major penetrations of the hull (e.g. for "Saildrive" propulsion units)

a) The mean laminate engineering constants and the thickness of a laminate are:

$$E_{x,laminate} = \frac{\sum E_{xi} \cdot t_i}{\sum t_i}; \; E_{y,laminate} = \frac{\sum E_{yi} \cdot t_i}{\sum t_i}; \; G_{xy,laminate} = \frac{\sum G_{xyi} \cdot t_i}{\sum t_i}; \; t_{laminate} = \sum t_i$$

$E_{xi,yi}; G_{xy,I}$ = engineering constants of layer
t_i = thickness of layer

These mean values should only be used for in-plane assessments or for very homogeneous layups:

b) Neutral axis z of an unsymmetrical laminate, measured vs. a reference axis:

$$z = \frac{\sum E_i \cdot t_i \cdot z_i}{\sum E_i \cdot t_i}$$

E_i = Young´s modulus layer in relevant direction

z_i = distance of layer centroid from reference axis

Note that the neutral axes of a laminate can be dissimilar in different directions.

c) Flexural stiffness EI of a single skin laminate per unit width:

$$EI = \sum E_i \cdot \left(\frac{t_i^{\,3}}{12} + t_i \cdot e_i^{\,2}\right)$$

e_i = distance of layer centriod from neutral axis of laminate

Note that the flexural stiffness of a laminate can be dissimilar in different directions.

d) The in-plane shear stiffness GA_u of a single skin laminate per unit width:

$$GA_u = \sum G_i \cdot t_i$$

If the shear stiffness per unit width is not applicable but the shear stiffness of a whole plate, the relevant plate width needs to be accounted for additionally.

$$GA = \sum G_i \cdot t_i \cdot w$$

w = plate width

3.3.3.5.2 Sandwich laminates

In the sense of this methodology, "sandwich" is considered to be an effective structural arrangement of materials with significantly different stiffness characteristics, where however the sandwich core shall have a sufficient amount of shear stiffness to allow for simplifications made in elemental beam theory.

Thus, the flexural and in-plane shear stiffness of a sandwich laminate is calculated like for single skin laminates, taking into account the core as an elementary layer with its particular thickness and modulus.

3.3.3.6 Beam analysis

Beams are structural elements that are mainly subjected to bending moments and also to shear forces when loaded laterally. In general, the associated plating contributes to stiffness and strength. Stiffeners, frames and girders can be considered as beams in this sense.

The following assumptions imply that the beams perform "plane bending", i.e. that the neutral axis of the beam with associated plating is parallel to the axis about which the assembly bends; the beam assembly is symmetrical about the axis which is perpendicular to the plating.

3.3.3.6.1 Effective width of plating

The following approach provides an indication about the effective width of plating. This is based on the assumption that the associated plating has near-quasi-isotropic in-plane properties. It may be adopted for reasonably balanced in-plane stiffness laminates.

The effective width of plating w_{eff} is taken as being dependant on the ratio L_1/w solely. The width of plating to account for when determining the beams stiffness can be taken from Figure 3-3 as a fraction of w.

L_1 is the length between zero bending moments of a beam between supports and is determined as follows:

L_1 = unsupported span for beams with hinged end supports 0.4 times the unsupported span for beam with ends fixed

w = plate width

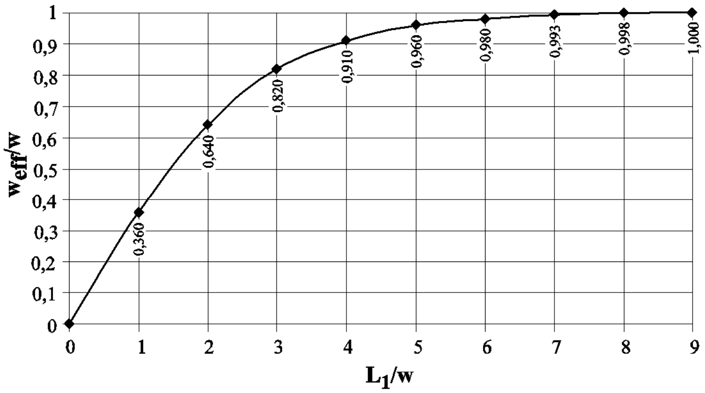

Figure 3-3 Effective width of plating

Additionally the beams foot width "w_f" can be added to w_{eff}, see Figure 3-4.

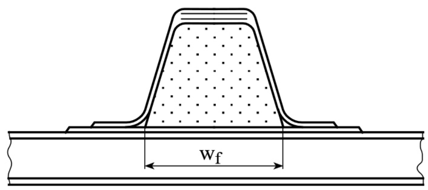

Figure 3-4 Typical top hat stiffener

The calculated effective width shall not be taken greater than the load width.

3.3.3.6.2 Flexural stiffness

$$EI = \sum E_i \cdot (I_i + S_i \cdot e_i^2)$$

E_i = tensile modulus of element

I_i = specific moment of inertia of element

e_i = distance of element’s centroid from neutral axis of assembly

S_i = cross sectional area of element

3.3.3.6.3 Shear stiffness

For determining the shear stiffness of a beam assembly, usually only the shear webs are accounted for.

$$GA = \sum G_i \cdot t_i \cdot h_i$$

t_i = web thickness

h_i = height of web measured perpendicular to associated plating

G = in-plane shear modulus of element

3.3.4 Laterally loaded plates

3.3.4.1 Applicability

In the following the structural design requirements for laterally loaded shells and plates are given. Lateral loading is usually caused by static or dynamic sea or water pressure (slamming) of hull shells, decks, superstructure, watertight bulkheads, tank walls etc.

The methodology presented in the following is covering flat or slightly curved panels of generally square or rectangular geometry with different boundary conditions. Other geometries (e.g. triangular or trapezoid styled) require an equivalent approach.

Plates considered here are generally laminated as single skin or sandwich panels.

It is recommended that elasto-mechanical properties of inner and outer sandwich skin do not differ significantly. This is to avoid secondary effects, such as superimposed twist or bending in plates.

3.3.4.2 Scope

The following approaches are featuring the ideas and the background of the "plate theory". Membrane effects occurring due to curved shells are treated with a linear reduction coefficient. Further contribution, like calculated using other methods or FEA, will generally not be accepted.

3.3.4.3 Objective

The objective is to determine plate stresses and strains from bending moments and shear forces caused by lateral pressure. The problem of an all-side supported panel will effectively be reduced to a unit beam strip, by using appropriate coefficients. The evaluation of stresses/strains is focussing on the spot where the maximum bending stress/strain occurs and a spot where the maximum through-thickness shear stress/strain occurs. Further to that, a correction is incorporated to allow the use of orthotropic material and plate properties and the application to sandwich construction.

If not explicitly mentioned, unit consistent variables shall be used.

3.3.4.4 Parameters

Laminated plates shall be characterised by the following parameters:

3.3.4.4.1 Structural parameters

EI_x = panel bending stiffness in panels global x-direction (about panels global y-direction)

EI_y = panel bending stiffness in panels global y-direction (about panels global x-direction)

t_c = thickness of sandwich core

z_i = distance from a certain location of the neutral axis in bending

These values are calculated in [3.3.3.4] or [3.3.3.3].

3.3.4.4.2 Geometrical parameters

s_x = unsupported span in global x-direction

s_y = unsupported span in global y-direction

Boundary conditions: all edges fixed or all edges simply supported

3.3.4.4.3 Load details and design pressures

Lateral design pressures acc. to relevant rules and guidelines.

3.3.4.4.4 Geometric aspect ratio ar_g

$$ar_g = \frac{s_x}{s_y}$$

3.3.4.4.5 Effective aspect ratio

For orthotropic panel properties with EI_x not equal EI_y, the geometrical aspect ratio ar_g needs to be corrected:

$$ar_{corr} = ar_g \cdot \sqrt[4]{\frac{EI_y}{EI_x}}$$

For the purpose of further calculations, the corrected aspect ratio ar_{corr} shall be related to the span of the panel that is considered to be effective to take up the major bending and shear loads (see [3.3.4.1]) and will be called "effective span s_{eff}":

ar_{corr} is > 1, then $ar_{eff} = ar_{corr}$.

Thus, the panel effective span s_{eff} (direction of main load take-up) runs in x-direction.

ar_{corr} is < 1, then $ar_{eff} = 1/ar_{corr}$

Thus, the panel effective span s_{eff} (direction of main load take-up) runs in y-direction.

3.3.4.4.6 Edge support boundary conditions and corrections

Generally, panels which are continuous over their supporting structure can be assumed providing a fixed edge boundary condition, whereas panels e.g. butting against a sandwich panel will be considered with edge condition "simply supported". Similar considerations should be carried out for great variations in neighbouring panel sizes.

In specific cases, hull chine’s or other sudden changes in geometry may be considered being a boundary as well. Should a chine be considered presenting one edge of a panel, the angle of the chine ω shall be close to 90° to allow for such assumption, see Figure 3-5. Should the angle be greater than 90°, the panel span taken for panel calculations needs to be increased virtually, using the characteristic correction factors described below.

The panel span which is delimited by a chine shall be multiplied by the correction factor c_s:

$s_{x/y}$	=	corrected panel span
		$c_s \cdot s_c$
c_s	=	correction factor
s_c	=	panel span

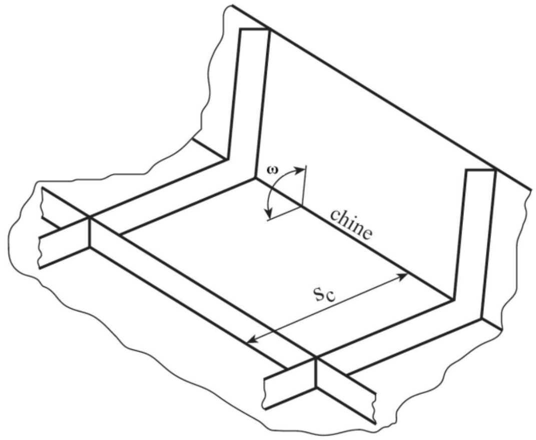

Figure 3-5 Corrected span

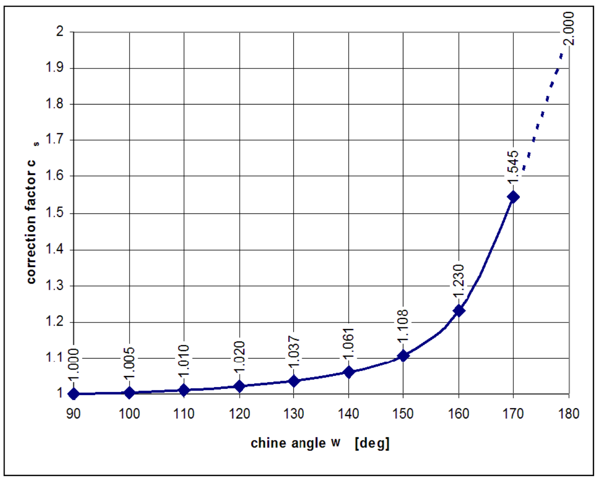

Figure 3-6 Panel span correction factor s_c dependant on chine angle

This correction is particularly applicable for equidistant spacings of panels, i.e. for panels on both sides of vessel's chined centreline without the existence of a centreline girder, e.g. where the panels are delimited by off-centre longitudinals. For determination of s_c see Figure 3-6.

3.3.4.4.7 Plate curvature

Curvature will only be considered if the plate is curved in the direction of the effective span s_{eff}, see Figure 3-7.

Plate curvature correction coefficient:

$$r_c = 1.15 - \left(5 \cdot \frac{h}{s_{eff}}\right)$$

where:

$$0.03 < \frac{h}{s_{eff}} < 0.1$$

and:

$r_{c,min}$ = 0.65

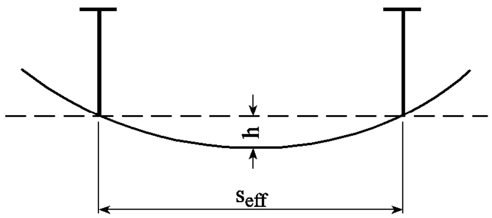

Figure 3-7 Plate curvature

3.3.4.5 Maximum bending moment, shear force and lateral deflection of panel

As mentioned in [3.3.4.1], the calculation is being reduced to the assessment of a panel strip of one unit width (e.g. 1 mm).

Table 3-2 Effective aspect ratio

For all edges simply supported										
ar_{eff}	1	1.2	1.4	1.6	1.8	2	3	4	5	∞
β	0.2874	0.3762	0.453	0.5172	0.5688	0.6102	0.7134	0.741	0.7476	0.75
α	0.0444	0.0616	0.077	0.0906	0.1017	0.111	0.1335	0.14	0.1417	0.1421
γ	0.42	0.455	0.478	0.491	0.499	0.503	0.505	0.502	0.501	0.5
For all edges fixed										
ar_{eff}	1	1.2	1.4	1.6	1.8	2	∞			
β	0.3078	0.3834	0.4356	0.468	0.4872	0.4974	0.5			
α	0.0138	0.0188	0.0226	0.0251	0.0267	0.0277	0.0284			
γ	0.42	0.455	0.478	0.491	0.499	0.503	0.5			

3.3.4.5.1 Maximum bending moment

$$M_{b-\max} = \frac{\beta \cdot p_d \cdot s_{eff}^2}{6} \cdot r_c$$

β = = see Table 3-2

p_d = lateral design pressure on associated plating according to Sec.2 [2.2.5].

s_{eff} = effective panel span

r_c = curvature correction coefficient

3.3.4.5.2 Maximum reaction shear force

$$F_{q-\max} = \gamma \cdot p_d \cdot s_{eff}$$

γ = = see Table 3-2
p_d = lateral design pressure on associated plating according to Sec.2 [2.2.5].
s_{eff} = effective panel span

3.3.4.5.3 Maximum lateral deflection

$$z_{\max} = \frac{\alpha \cdot p_d \cdot s_{eff}^4}{12 \cdot EI_{eff}}$$

α = see Table 3-2
p_d = lateral design pressure on associated plating according to Sec.2 [2.2.5].
s_{eff} = effective panel span
EI_{eff} = plate bending stiffness relevant for the direction of the effective panel span

3.3.4.6 Determination of laminate strains and stresses

3.3.4.6.1 Laminate strains

The structural performance of a laterally loaded plate is characterised by the occurring strains in the laminate using the following approach.

Resulting strains at a distance of z_i from the plate's neutral axis:

$$\varepsilon_i = \frac{M_{b-\max} \cdot z_i}{EI_{eff}}$$

The maximum strains through bending moments usually emerge at the outer surfaces of a composite. Hence, for evaluating the maximum strains, use the maximum distances from the neutral axis at each side of the plate.

The calculated strains may not exceed the allowable defined in [3.3.9]. Apart from the pure bending strains, stability issues such as skin wrinkling need to be considered, relate to [3.3.7].

3.3.4.6.2 Determination of core shear stresses in sandwich laminates

Whereas with solid coreless laminates, the through-thickness interlaminar stress is rarely a design criterion, it is so for most of the lower density/strength cores of a typical sandwich. The core shall transmit the through-thickness shear forces. A certain contribution by the skins is assumed.

Core shear stress is calculated as being:

$$\tau_c = \frac{F_{q-\max}}{t_c + \frac{t_{s1}}{2} + \frac{t_{s2}}{2}}$$

$F_{q\text{-}max}$ = see [3.3.4.3.2]
t_c = core thickness
t_{s1}, t_{s2} = skin thickness

The calculated stresses may not exceed the allowable defined in [3.3.9].

3.3.5 Laterally loaded beams

3.3.5.1 Applicability

The following approach can be used for laterally loaded beams, stiffeners, frames and girders, with or without associated plating attached. These structural members are usually part of an orthogonal structural system of a vessel. In well found cases, curvature effects may be taken into account in a similar way as shown for panels, see Figure 3-8.

Typically, the beams consist of a web designed to carry the shear force and two flanges to carry the bending load, both generated by lateral pressure.

The web may be attached vertically or inclined to the attached shell (only the structural height times the thickness as effective shear area shall be considered). One flange is usually presented by a certain amount of attached plating (see effective width) and possible additional pads beneath the web. The other flange is presented by the "capping" of the beam.

Beams should be designed in a way that the transfer of loads is fibre dominant. In general this will require shear webs to consist of ±45° layers of laminate, whereas the flanges consist of a certain number of 0° plies. However, it shall be taken into account that shear loads can be transferred from the flange into the web.

The following approaches are featuring the partly simplified "Classical Laminate Theory" and the simple "Beam Theory".

The objective is to determine beam stresses and strains from bending moments and shear forces caused by lateral pressure on the associated plating. The computational model is presented by a simple beam with appropriate support conditions.

In case the scantlings are constant over the full length of the beam, it is sufficient to evaluate stresses and strains, respectively, through

— bending moment and shear force at the end of the beam for a support condition "ends fixed"
— bending moment at the centre of the beam and shear effects at the end of the beam for a support condition "ends simply supported"

Laminated beams may have a great variety of section shapes. Generally it is recommended to use symmetrical or near-symmetrical section shapes, as unsymmetrical shapes are subjected to superimposed secondary effects such as transverse bending or a twisting of the beam (flange). This makes a more refined analysis necessary than offered below.

Guidance note:

Due to the resulting transverse bending moment occurring in the flange, L-section beams with common width to height ratio show up to 2-times the calculated strains/stresses compared to calculated using the below approach. Measures shall be taken to reduce the strains by increasing the flange scantlings, or mounting tipping brackets along the beam.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

If not explicitly mentioned, use consistent unit variables.

Laminated beams including their associated plating shall be characterised by the following parameters:

3.3.5.2 Parameters

3.3.5.2.1 Structural parameters

The following parameters have been determined in [3.3.3.6]:

EI = beam bending stiffness including associated plating

GA = shear stiffness of webs
z_i = distance from a certain location within the beam to the neutral axis in bending
w_{eff} = effective width of plating

3.3.5.2.2 Geometrical parameters

l = unsupported length of the beam
w = load width

3.3.5.2.3 Load details

For panel design pressures see Sec.2

3.3.5.2.4 Beam curvature correction

Curvature correction coefficient:

$$r_{cb} = 1.15 - \left(5 \cdot \frac{h}{\ell}\right)$$

Where:

$$\text{for: } 0.03 < \frac{h}{\ell} < 0.1$$

and:
$r_{cb,min}$ = 0.65

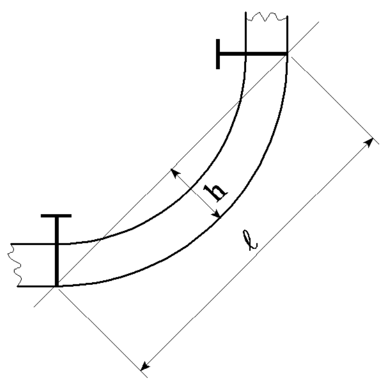

Figure 3-8 Beam curvature definitions

3.3.5.3 Maximum bending moment, shear force and lateral deflection of beam

3.3.5.3.1 Maximum bending moment

$$M_{b-max} = \frac{P_d \cdot w \cdot l^2 \cdot r_{cb}}{c_b}$$

P_d = lateral design pressure on associated plating acc. to Sec.2 [2.2.5]

r_{cb} = beam curvature reduction factor see [3.3.5.2.4]

c_b = boundary condition coefficient

12 for fixed end supports

8 for simply supported

3.3.5.3.2 Maximum reaction shear force

The maximum shear force typically occurs at the boundaries:

$$F_{q-max} = \frac{P_d \cdot l \cdot w}{2}$$

P_d = lateral design pressure on associated plating according to Sec.2 [2.2.5]

3.3.5.3.3 Maximum lateral deflection

The maximum lateral deflection of a beam is typically observed half way along the beam, considering that both ends have similar end support conditions and the beam has constant structural section and material properties along its length:

$$z_{max} = \frac{P_d \cdot w \cdot l^4 \cdot c_d}{384 \cdot EI}$$

P_d = lateral design pressure on associated plating according to Sec.2 [2.2.5]

c_d = boundary condition coefficient

= 1 for fixed end supports

= 5 for simply supported

3.3.5.4 Beam construction notes

3.3.5.4.1 In general, the bonding laminate (if not integral with the shear web) of a shear web shall have the same shear stiffness/strength as the web. The lap of the bonding shall be large enough to transmit in-plane shear forces. It is important to place the bonding tapes using the specified fibre orientations throughout, see Figure 3-9.

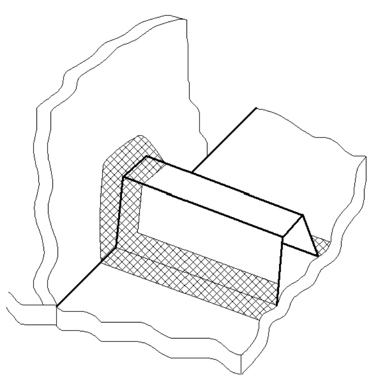

Figure 3-9 Bonding of a beam to adjacent structure

This is not only applicable to the bond between the beam and the associated plate but also to the bond between the beam and the next higher hierarchical member in structure, which it is supported by.

3.3.5.4.2 The requirement for a sufficient amount of shear buckling stiffness of web laminates may lead to the inclusion of stabilising measures for webs (e.g. sandwich web or foam filled). If webs are of single skin style, the web height may not exceed 30 times the web thickness or the thickness shall be greater than 1/30 of the web height to prevent shear buckling.

3.3.5.4.3 In special cases it may be required to replace the core of the associated plate with a higher strength/ stiffness shear tie.

3.3.5.4.4 Web laminates necessary to carry the shear loads should in general continue across the capping laminate and be interspersed with the capping laminate.

3.3.6 Determination of laminate strains and stresses

3.3.6.1 General

The structural performance of a laterally loaded beam is characterised by the occurring strains in the laminate. The maximum bending strains usually emerge at the most external areas of the composite. The most critical shear loading can usually be found in the shear webs.

3.3.6.2 Strains and stresses

3.3.6.2.1 In-plane uniaxial strains

Resulting bending strains at a distance of e_i from the beam’s neutral axis:

$$\varepsilon_i = \frac{M_{b-max} \cdot e_i}{EI}$$

For evaluating the maximum strains, the maximum distances e_i from the neutral axis at each side of the beam shall be used. Due to special configurations, materials or geometries it might be necessary to calculate the strains at other characteristic locations along the beam.

The calculated strains may not exceed the allowable defined in [3.3.9].

3.3.6.2.2 In-plane shear strains in webs

$$\gamma_s = \frac{F_{q-max}}{GA}$$

The calculated strains may not exceed the allowable defined in [3.3.9].

3.3.7 Stability considerations

3.3.7.1 Skin wrinkling of sandwich skins

Skin wrinkling of sandwich skins may be critical especially in cases where a sandwich panel is subjected to bending so that one skin is in compression. Depending on the stiffness of the laminate in the relevant direction and on the supporting properties of the core, the following approach is used to assess strains above which skin wrinkling is expected:

$$\varepsilon_{sw-crit} = \frac{1}{2} \cdot \frac{\sqrt[3]{(E_x \cdot E_{cc} \cdot G_c)}}{E_x}$$

E_x = laminate Young's modulus in direction of compression
E_{cc} = core's Young's modulus in compression
G_c = core's shear modulus

The strains determined this way shall be at least 2.5 times greater than the general allowable defined in [3.3.9].

3.3.7.2 Buckling of orthotropic plates under uniaxial membrane loads

3.3.7.2.1 Considerations and limitations

The buckling of sandwich panels needs to be considered for global in-plane compression and in-plane shear.

The following methodology is based on simplified classical laminate theory, i.e. only valid for laminate plates (sandwich or single skin) which are well balanced through thickness. Only sandwich laminates with skin in-plane tensile stiffness (E · t) difference of no more than 20% in each direction x or y may be considered this way:

$$0.8 \le \frac{E_{x-os} \cdot t_{os}}{E_{x-is} \cdot t_{is}} \le 1.2$$

and:

$$0.8 \le \frac{E_{y-os} \cdot t_{os}}{E_y \cdot t_{is}} \le 1.2$$

where "os" and "is" are indices for "outer skin" and "inner skin".

Also, all edges need to be supported. There is no implementation for the possibility to calculate plates with one free edge.

This condition presumes that there will be no or only minor coupling between in-plane and out-of-plane effects.

3.3.7.2.2 Critical buckling strain

For arbitrary boundary conditions the critical membrane strain of an orthotropic plate that leads to buckling is:

$$\varepsilon_{B-crit} = \frac{1}{E_{a-mean} \cdot t_{tot}} \cdot k_x \cdot \left(\frac{\pi}{b}\right)^2 \cdot \sqrt{D11 \cdot D22}$$

$E_{a\text{-}mean}$ = mean Young's modulus in load direction (a) of full laminate (incl. core)
t_{tot} = total thickness of full laminate (incl. core)
b = plate width perpendicular to load direction
a = plate width parallel to load direction
k_x = buckling coefficient:

$$= h(\overline{\alpha}) + q \cdot \beta$$

q = boundary condition adjustment factor

= 2 for unloaded edges simply supported

= 2.36 for unloaded edges clamped

$h(\overline{\alpha})$ = see Figure 3-10

$\overline{\alpha}$ = modified aspect ratio:

$$= \frac{a}{b} \cdot \sqrt[4]{\frac{D22}{D11}}$$

β = "Seydel" orthotropic parameter:

$$= \frac{D12 + 2 \cdot D33}{\sqrt{D11 \cdot D22}}$$

Coefficients from the laminate’s bending matrix D:

$$D11 = \sum_{i=1}^{n} Q11'_{Li} \cdot \frac{1}{3}(z_i^3 - z_{i-1}^3)$$

$$D12 = \sum_{i=1}^{n} Q12'_{Li} \cdot \frac{1}{3}(z_i^3 - z_{i-1}^3)$$

$$D22 = \sum_{i=1}^{n} Q22'_{Li} \cdot \frac{1}{3}(z_i^3 - z_{i-1}^3)$$

$$D33 = \sum_{i=1}^{n} Q33'_{Li} \cdot \frac{1}{3}(z_i^3 - z_{i-1}^3)$$

Index "i" stands for each particular layer of a total of "n" layers of a laminate.

$Q11'_L$, $Q12'_L$, $Q22'_L$ and $Q33'_L$ are coefficients determined in [3.3.4.2].

z_i are distances from ply surfaces to the laminate midplane as depicted in Figure 3-2.

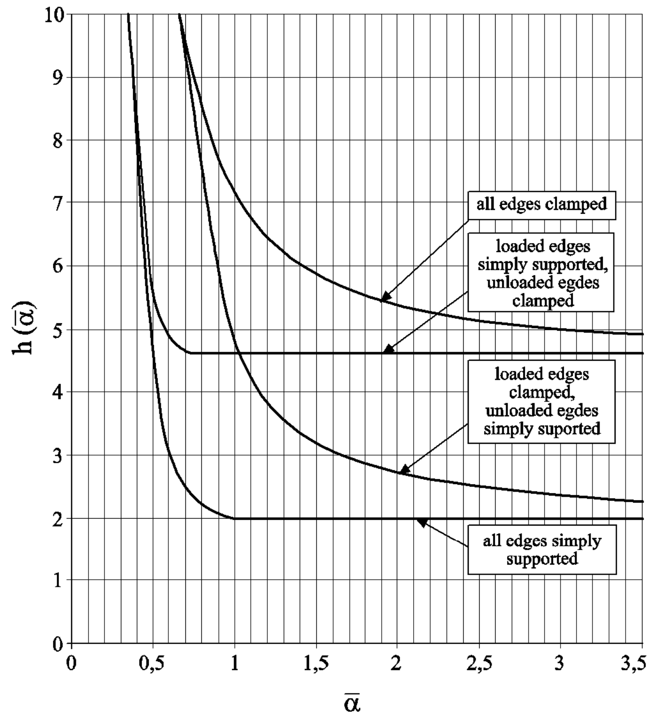

Figure 3-10 Simplified h$(\overline{\alpha})$ curves

3.3.7.3 Buckling of orthotropic plates under in-plane shear loads

The general provisions [3.3.7.2] apply.

3.3.7.3.1 Critical buckling strain

For an all-sided simply supported orthotropic plate, the critical in-plane shear strain that leads to buckling is:

$$\gamma_{B\text{-}crit} = \frac{1}{G_{a\text{-}mean} \cdot t_{tot}} \cdot K_S \cdot \left(\frac{\pi}{w}\right)^2 \cdot \sqrt[4]{D_a \cdot D_b^{\ 3}}$$

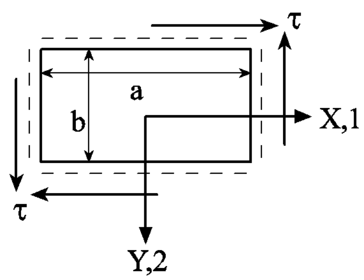

Figure 3-11 Nomenclature

$G_{a\text{-}mean}$ = mean in-plane shear modulus of full laminate

t_{tot} = total thickness of full laminate
w = plate width a or b, see below
k_S = buckling coefficient, as per Figure 3-12
β = Seydel orthotropic parameter

$$= \frac{D12 + 2 \cdot D33}{\sqrt{D11 \cdot D22}}$$

α = modified inverse aspect ratio

$$= \frac{1}{\bar{\alpha}} = \frac{b}{a} \sqrt[4]{\frac{D11}{D22}}$$

If $\alpha \leq 1$, then

w = b
D_a = D11
D_b = D22

If $\alpha > 1$, then

α = $\bar{\alpha}$
w = a
D_a = D22
D_b = D11
b = plate width in X,1 direction
a = plate width in Y,2 direction

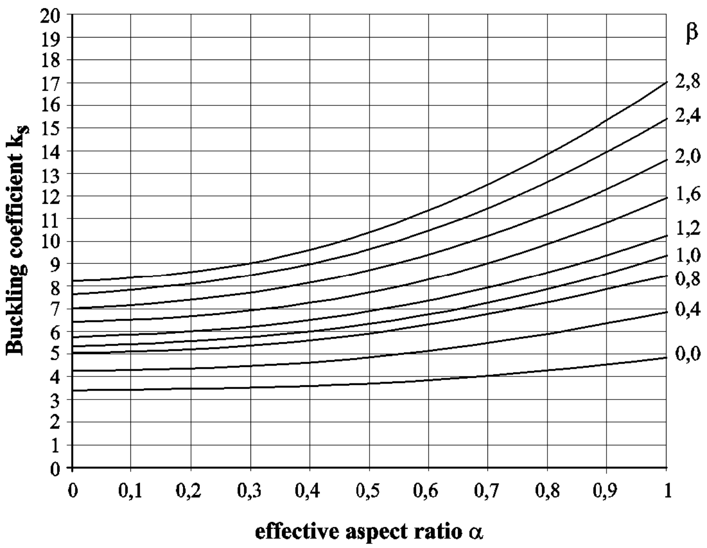

Figure 3-12 Buckling coefficient k_s

3.3.8 Further considerations

3.3.8.1 Through-thickness effects

In general it is preferred to have a fibre-dominant load absorption in a composite structure, but in some cases it will be unavoidable that through thickness effects occur. Those structural details will be treated individually and case by case.

3.3.8.2 Minimum shell thickness

No particular algorithm has been implemented to determine a minimum shell or skin thickness for hull laminates. As global strength and stiffness criteria have been set, a remaining issue is that of a shell laminate being prone to local forces or impact when docking, dry docking or from collision with floating or submerged debris. This subject will be handled individually.

3.3.9 Allowable strains, safety factors and maximum deflections

For fibre reinforced composite components, the "maximum strain criteria" is mainly used to assess the structural integrity. This criterion may solely be used in association with the provisions described and defined so far.

This criterion is providing an appropriate limit for fibre reinforced composites under the condition that the composite shows a fibre-dominant load transfer.

These limits provide a sufficient margin over interlaminar micro cracking and fibre failure in all in-plane directions.

For adhesive bonds, the structural evaluation of sandwich cores and evaluation of stability criteria, safety factors are serving to achieve sufficient integrity. Further to that, a deflection criterion shall be fulfilled.

3.3.9.1 Limit laminate strains

Maximum allowable strain of 0.25% for carbon laminates (accounts for standard modulus and hi strength carbon fibres)

0.35% for E-glass laminates in tension and compression, respectively.

Maximum allowable in-plane shear strain shall be:

0.45%	(for carbon laminates)
0.7%	(for E-Glass laminates)

3.3.9.2 Sandwich core safety factors

Safety factor of 2.5 vs. core shear failure (linear shear stress distribution over the core and each half of the skins). Basis are the values approved by DNV GL or the "msmv" (manufacturer specified minimum values) values for structural cores.

3.3.9.3 Safety factors and limit deflections

— Appropriate safety of skin/core bond
— Factor of 2.5 vs. panel buckling and 2.0 vs. skin wrinkling on the strains determined according to 3.5
— Factor of 2.5 vs. ultimate shear strength in adhesive bond using well-proven structural adhesives
— Maximum permissible lateral deflections under lateral load:
    — 1.5% of effective panel span for single skin laminate panels
    — 1.0% of effective panel span for sandwich panels
    — 0.5% of unsupported span of a stiffener or girder
    — 0.3% of unsupported span of engine foundation.

3.3.10 Construction and design details

3.3.10.1 Consequences of elasticity

Fibre reinforced composites used for marine applications exhibit almost linear elastic behaviour to failure. This is as long as the structural response is fibre-dominated, which is preferred over a matrix dominant behaviour. Respecting this, composites show little or no yielding until failure. This aspect requires particular attention. Especially in structural details with occurring stress concentrations, consideration shall already be given in static strength analysis. In cases in which these concentrations are compensated appropriately, fatigue will not be critical. This is valid for in-plane loads with fibre dominated load absorption. However, through-thickness loading (especially shear and tension) cannot always be avoided and yet needs to be handled in an appropriately conservative way. "Intercracking" or delamination caused by overloading, impact or deficient structural design is considered to be the cause for subsequent failure of components and thus can be deemed as cause for fatigue with composites.

3.3.10.2 Recommendations

The following recommendations do not claim to be all-inclusive and are subject to up-date/change/ amendment:

- In general, the basic laminate stacking sequence shall be homogeneous; preferably symmetrical and balanced, if not particular attention shall be paid to possible arising secondary affects.
- A laminate should consist of plies aligned in at least 4 distinct directions (e.g. 0°, +/-45°, 90°), with not less than 10% in each direction. Ply angles should be aligned appropriately for major load direction(s). Exemptions are the following components/items:
  - mainly in-plane shear loaded webs of girders, stiffeners, frames
  - local tape reinforcements
  - Grouping of plies with the same fibre direction should be avoided, but total thickness of these plies may not exceed 1.5 mm (typically for carbon laminates).
  - Not all parts are suitable for composites. Complex 3-dimensional stress states may make suitable isotropic materials a preferred choice (e.g. local fittings).
  - Inaccessibility of composite components needs to be considered in design in terms of inspectability during production, in-service and after damage.

3.3.10.3 Details

All structural details are subject to examination by DNV GL. In general the following provisions shall be observed.

3.3.10.3.1 The occurrence of peeling effects, such as abrupt stiffness changes shall be minimized. Secondary bonding is always to be backfilled with suitably coved filler bed.

3.3.10.3.2 For mechanical fastenings, a domination of fibre orientation in one direction of more than 40% is not advisable.

3.3.10.3.3 Core chamfers of sandwich laminates should not be steeper than 1:3 thickness/taper ratio.

3.3.10.3.4 Exposed fibres and sandwich cores shall be sealed or clashed with laminate

In panels where there is a change from sandwich to single skin laminate (e.g. in hull to deck joints), the required single skin laminate shall be determined by the scantlings for the whole panel.

3.3.10.3.5 Changes of thickness for a single-skin laminate shall be made as gradually as possible and over a width which is, in general, not to be less than thirty times the difference in thickness.

3.3.10.3.6 The connection between a single-skin laminate and a sandwich laminate shall be carried out as gradually as possible over a width which is, in general, not to be less than three times the thickness of the sandwich core.

3.3.11 Structural metal parts

3.3.11.1 General

For design loads of metallic keel arrangements see Sec.2 [2.3] [2.3].

3.3.11.2 Allowable stresses for metallic parts of the keel

$$s_{all} = s_{lim} \cdot k_{mat} \cdot k_{lc} \quad [N/mm^2]$$

s_{lim} = yield stress or 0.5 · ultimate stress, whichever is lower in accordance with EN ISO 6892-1 or similar

for metals less than 30 mm from welding seams the mechanical properties in welded condition shall be used.

k_{mat} = 0.75 for ductile metals

0.75 · (0.0263 · ε + 0.474) for brittle metals

ε = elongation at break in accordance with EN ISO 6892-1 or similar brittle metals have an $\varepsilon \leq 20\%$

k_{lc} = 0.80 for keel bolts for LC1

1.10 for keel bolts for LC2 and LC3

0.96 for keel elsewhere for LC1

1.10 for keel elsewhere for LC2 and LC3

3.3.12 Keel fatigue assessment

Relate to ISO 12215-9.

CHANGES – HISTORIC

There are currently no historical changes for this document.