7 Guidelines for the Structural Design of Racing Yachts ≥ 24 m
The following Guidelines come into force on 1 December 2012.

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## Table of Contents

### Section 1 General Requirements
- A. Application, Scope .......................................................... 1- 1
- B. Documents for Approval .................................................. 1- 2
- C. Definitions ............................................................................. 1- 3

### Section 2 Materials
- A. Fiber Reinforced Plastics, Sandwich Constructions and Bonding .................................. 2- 1
- B. Steel Alloys ............................................................................. 2- 1
- C. Aluminium Alloys ................................................................. 2- 2
- D. Welding .................................................................................. 2- 4
- E. Corrosion protection ............................................................... 2- 5
- F. Cold-molded Wood and Bonding .......................................... 2- 6

### Section 3 Design Loads
- A. General ............................................................................... 3- 1
- B. Lateral Design Pressures ..................................................... 3- 1
- C. Design Loads for Keel and Keel Attachments ...................... 3- 4
- D. Rudder Design Loads ............................................................ 3- 4
- E. Global Loads ........................................................................... 3- 6

### Section 4 Design and Scantlings for Composite Structures
- A. General ............................................................................... 4- 1
- B. Principles for Structural Design ............................................. 4- 1
- C. Scantlings ............................................................................... 4- 3

### Section 5 Design and Scantlings for Steel and Aluminium Structures
- A. General ............................................................................... 5- 1
- B. Principles for Structural Design ............................................. 5- 1
- C. Scantlings ............................................................................... 5- 6

### Section 6 Design and Scantlings for Steel Structures of Yachts L ≥ 48 m
- A. General ............................................................................... 6- 1
- B. Materials ............................................................................... 6- 1
- C. Scantlings ............................................................................... 6- 1

### Section 7 Chainplates and Propeller Brackets
- A. General ............................................................................... 7- 1
- B. Chainplates and substructures ............................................. 7- 1
- C. Propeller brackets ................................................................. 7- 2
Annex A Keel Fatigue Assessment

A. General ........................................................................................................................................ A-1
B. Fatigue Strength Analysis for Free Plate Edges and for Welded Joints Using Detail Classification .............................................................................................................. A-5
C. Fatigue Strength Analysis for Welded Joints Based on Local Stresses ........................................ A-8
Section 1

General Requirements

A. Application, Scope

1. Application

1.1 These Guidelines apply to seagoing monohull sailing yachts with a hull length of 24 m and over (measured in accordance with ISO 8666) for competitive racing and recreational use, provided that the yacht, approved in accordance therewith, is at all times employed exclusively under the conditions for which it has been designed, constructed and approved and that it is equipped and handled in the sense of good seamanship, and operated at a speed adopted to the respective wind and sea conditions.

2. Scope

2.1 These Guidelines envisage primarily structural integrity of yacht’s hull made of metallic materials or fiber reinforced polymer composites including structural components listed in 3.2. Any note in this Guideline addressing issues other than structural integrity is to be considered as recommendation or guidance to designer, builder, owner, et al.

Design of wooden hulls will be treated individually.

2.2 Aspects which go beyond the scope of a structural design assessment are written in Italics, and may yet serve as reference and/or recommendation.

The requirements of these Guidelines do not substitute the independent judgment of professional designers. This is particularly valid for those aspects not addressed in these Guidelines and for which the designers are solely responsible.

2.3 Equivalence

Yachts deviating from the requirements of these Guidelines in their type or design may be approved, provided that their structures are recognized to be equivalent to GL's requirements.

2.4 Confidentiality

Amongst other aspects, confidentiality is regulated in GL Rules for Classification and Surveys (I-O-0), Section 1, D.

3. Scope of plan approval

3.1 Objectives

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. For this purpose, longitudinal strength check will be carried out as well as analysis of more local structural design.

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

3.2 Scope and depth of review

Indicative list of typical items addressed in plan review:

- Hull shell, deck shell, girders and stiffeners, frames, ring frames, bulkheads, decks, soles, integrated tanks, stern and transom, joining of components, global and local reinforcements
- Foundations: Main engine foundations
- Keel arrangement, keel bulb, keel fin and its structural attachment to hull; hull structure in way of keel attachment
- Rudder incl. shaft, shaft bearings and their structural integration
- Propeller bracket incl. structural attachment and foundation
- Chain plates of standing rigging elements, mast step foundation
- Structural details such as: window mullions, pillars, hatch panels (if integral), cut-outs, under water trough-hull penetration design, structural recesses
- Structural attachments of primary structural members as listed above

Items typically not included in plan review:

- Foundations such as of anchor windlass, generators, pumps, safety equipments, mooring equipment and/or similar
- “Lower” priority details and/or equipment such as: manholes, access cover details, railings, mooring cleats, doors and hatches (provided not integral), platforms or ducts, ladders, stair cases and roofs if not integral with main structures
- Non-structural partitions and components
- Strong points such as foundations for running rigging, mooring applications
- Watertight subdivision, closures, windows
4. General operating conditions

The structural design is to be based on ambient conditions typical to a worldwide unrestricted range of service, but up to winds and sea states according Beaufort 12 and ambient temperatures between -10 °C and +45 °C.

The same conditions are also applicable for all shipboard machinery, equipment and appliances.

5. Other GL Rules and Guidelines

For the design of the hull structures the following other GL Rules are available for guidance:

– GL Rules for Metallic Materials (II-1)
– GL Rules for Fibre Reinforced Plastics and Bonding (II-2-1)
– GL Rules for Wooden Materials (II-2-2)
– GL Rules for Welding (II-3)
– GL Rules for Yachts ≥ 24 m (I-3-2)

B. Documents for Approval

1. General requirements

1.1 All documents submitted to GL have to be in English or German language.

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 are to be explained in a key list. All documents shall show the project name, drawing number and revision number.

1.3 Submitted documentation about performed calculations shall contain all necessary information concerning reference documents, literature and other sources. The calculations have to 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.

1.4 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.

2. Guidance for submission of documents

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

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, GL provides a digital platform called GLOBE.

2.2.1 General information

– List of submitted drawings (title, drwg.no., date of latest revision)
– General Arrangement, Deck Plan, Sail Plan
– Technical specification (main dimensions, displacement, etc.)
– Material specifications

2.2.2 Structural components of the hull

– Structural members of the hull shown in side view, plan view and cross sections (bulkheads, frames, floors, etc.)
– Hull, decks and superstructure
– Bonding of structural components
– Hull to deck joint
– Drawing of mast pillar, mast step
– Chain plates
– P-brackets

2.2.3 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
– Flange area of keel-hull connection
– Material specification of keel bolts and diameter
– Anchoring of bolts in the keel
– Typical keel foil sections
– Specification of welding

If the keel is not a bolted keel, documents are to be submitted accordingly, to a similar depth of detailing.

2.2.4 Rudder design

– Rudder general arrangement
– Geometry of rudder
C. Definitions

1. Definitions

1.1 Principal dimensions

1.1.1 Length L [m]

The length L of the yacht is the length of the design waterline at displacement Δ.

1.1.2 Breadth B [m]

The breadth B is the greatest molded breadth of the yacht.

1.1.3 Depth H [m]

The depth H is the vertical distance, at the middle of the length L, from the base line to top of the deck beam at side on the uppermost continuous deck. In way of effective superstructures, the depth is to be measured up to the superstructure deck for determining the yacht’s scantlings.

1.1.4 Hull draught T_H [m]

The hull draught T_H is the draught of the canoe body of the yacht at displacement Δ.

1.1.5 Baseline

The baseline is a line parallel to displacement Δ waterline, tangent to the point with the largest canoe body draft T_H.

1.1.6 Displacement Δ [t]

The displacement Δ is the weight of the yacht in seaworthy racing condition, including sails, equipment and crew, but without consumables and with empty fresh water and fuel tanks. If the yacht is carrying water ballast the weights of those ballast tanks have to be considered as completely filled that are most effective for upwind sailing.

1.1.7 Yacht’s speed v_0 [kn]

The yacht’s generic design speed v_0 is defined as:

\[ v_0 = 0.692 \cdot L^{0.333} \cdot c_v \cdot c_c \]

\[ c_v = \frac{L}{\rho \cdot \Delta^{0.333}} \], where \( 6.5 \leq c_v \leq 9.5 \)

\[ \rho = \text{density of water [to/m}^3\text{]} \]

\[ c_c = 0.385 \cdot \left( \frac{GZ \cdot L}{\Delta^{0.333}} \right)^{0.5} \], where \( c_{\text{min}} = 0.95 \)

\[ GZ = \text{is the maximum righting moment lever at heeling angles below 60°, with all stability-increasing devices such as canting keel, water ballast and crew, in their most effective position for upwind sailing, determined at displacement Δ.} \]

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**Fig. 1.1 Coordinate system and principle dimensions**
1.2 Definition of “hull”

The hull of a vessel in the terms of these guidelines is the floatation body up to a 45° tangent on the deck sheer line, but excluding the stern if inclined to horizontal more than 45°.

1.3 Definition of decks

1.3.1 Weather deck

All free decks and parts of deck exposed to the sea are defined as weather decks.

1.3.2 Sheltered deck

Decks which are not accessible to persons and which are not subject to sea pressure. Crew can access such deck with care and taking account of the admissible load, which is to be clearly indicated.

1.3.3 Accommodation deck

Accommodation deck is a deck which is not exposed to the sea and serves as a basis for usual crew or guest accommodation.

1.3.4 Superstructure

The superstructure elevates from the weather deck and includes front, back and side walls, coamings and decks.

2. Coordinate system

For the description of the yacht's geometry the fixed, right-handed coordinate system x, y, z as defined in Fig. 1.1 is introduced. The origin of the system is situated at the aft end of L, at centerline and on the molded baseline at the yacht's 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 the three axes.

3. Computational software

3.1 General

In order to increase the flexibility in the structural design of yachts, GL also accepts direct calculations using computational software. The aim of such analyses should be the proof of equivalence of a design with the rule requirements.

3.2 General programs

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

3.2.2 Direct calculations may be applied regarding:

- global strength
- longitudinal strength
- beams and grillages
- strength of structural details

3.2.3 For such calculations, the structural model, boundary conditions, load cases and applicable material allowables (strength, strain) are to be agreed upon with GL. Calculation documents are to be submitted including input and output. During the examination it may prove necessary that GL perform independent comparative calculations.
Section 2

Materials

A. Fiber Reinforced Plastics, Sandwich Constructions and Bonding

The GL Rules for Fibre Reinforced Plastics and Bonding (II-2-1) and, of this Guideline, Section 4, C. (Scantlings) serve as guide in addition to the below.

1. Acceptance of materials for plan approval

All materials to be used during production of components from FRP shall first be assessed by GL. A plan review does not require materials to be type approved. However, GL reserves the right to assess the reasonability of mechanical properties used for the design, handed in for review.

Material Type Approvals by other organizations can be recognized following agreement by GL, provided the respective acceptance procedure is similar to those of GL.

2. Properties of the materials

The basic properties of the different materials shall be verified by test certificates of a recognized testing body. These values shall fulfill the minimum requirements specified in the relevant GL Rules.

3. Processing and surveillance

3.1 All manufacturing facilities, store rooms and their operational equipment shall fulfill the requirements of the responsible safety authorities and professional employers liability insurance associations. The manufacturer is exclusively responsible for compliance with these requirements.

B. Steel Alloys

1. Steel types

1.1 Normal strength hull structural steel

Normal strength hull structural steel is a hull structural steel with a minimum nominal upper yield point $R_{el}$ of 235 N/mm$^2$ and a tensile strength $R_m$ of 400 – 520 N/mm$^2$.

1.1.1 When not mentioned explicitly the material factor $k$ in the formulae of Section 3, Section 4 and Section 7 is to be taken 1,0 for normal strength hull structural steel.

1.1.2 Normal strength hull structural steel is grouped into the grades GL–A, GL–B, GL–D, GL–E, which differ from each other in their toughness properties. For the application of the individual grades for the hull structural members see GL Rules for Yachts ≥ 24 m (I-3-2), Section 2, B.2.3.

1.1.3 If for special structures the use of steels with yield properties less than 235 N/mm$^2$ has been accepted, the material factor $k$ is to be determined by:

$$k = \frac{235}{R_{el}}$$

1.2 Higher strength hull structural steels

Higher strength hull structural steel is a hull structural steel, the yield and tensile properties of which exceed those of normal strength hull structural steel. For three groups of higher strength hull structural steels the nominal upper yield stress $R_{el}$ has been fixed at 315, 355 and 390 N/mm$^2$ respectively. Where higher strength hull structural steel is used, for scantling purposes the values in Table 2.1 are to be used for the material factor $k$ mentioned in Section 3, 4 and 7 of the following:

Table 2.1 Material factors for higher strength hull structural steel

<table>
<thead>
<tr>
<th>$R_{el}$ [N/mm$^2$]</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>315</td>
<td>0,78</td>
</tr>
<tr>
<td>355</td>
<td>0,72</td>
</tr>
<tr>
<td>390</td>
<td>0,66</td>
</tr>
</tbody>
</table>

For higher strength hull structural steel with other nominal yield stresses, the material factor $k$ may be determined by the following formula:

$$k = \frac{295}{R_{el} + 60}$$

Note

Especially when higher strength hull structural steels are used, limitation of permissible stresses due to buckling and fatigue strength criteria may be required.
Table 2.2  Designation and mechanical properties of austenitic stainless steels (in welded condition)

<table>
<thead>
<tr>
<th>Material number</th>
<th>Designation according to EN 10088</th>
<th>Sweden SS</th>
<th>USA AISI / SAE</th>
<th>Tensile strength $R_m$ [N/mm²]</th>
<th>Yield strength $R_{p0.2}$ [N/mm²]</th>
<th>Pitting resistance equivalent $W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4306</td>
<td>X2CrNi19-11</td>
<td>2333</td>
<td>340 L</td>
<td>500 ÷ 650</td>
<td>200</td>
<td>18</td>
</tr>
<tr>
<td>1.4404</td>
<td>X2CrNiMo17-12-2</td>
<td>2348</td>
<td>316 L</td>
<td>520 ÷ 670</td>
<td>220</td>
<td>23</td>
</tr>
<tr>
<td>1.4435</td>
<td>X2CrNiMo18-14-3</td>
<td>2353</td>
<td>316 L</td>
<td>520 ÷ 670</td>
<td>220</td>
<td>25</td>
</tr>
<tr>
<td>1.4438</td>
<td>X2CrNiMo18-16-4</td>
<td>2367</td>
<td>317 L</td>
<td>520 ÷ 720</td>
<td>220</td>
<td>27</td>
</tr>
<tr>
<td>1.4439</td>
<td>X3CrNiMoN17-13-5</td>
<td>-</td>
<td>-</td>
<td>580 ÷ 780</td>
<td>270</td>
<td>33</td>
</tr>
<tr>
<td>1.4541</td>
<td>X6CrNiTi18-10</td>
<td>2337</td>
<td>321 L</td>
<td>500 ÷ 700</td>
<td>200</td>
<td>17</td>
</tr>
<tr>
<td>1.4462</td>
<td>X2CrNiMo22-5-3</td>
<td>2324</td>
<td>329 L</td>
<td>640 ÷ 840</td>
<td>460</td>
<td>31</td>
</tr>
<tr>
<td>1.4571</td>
<td>X6CrNiMoTi117-12-2</td>
<td>2350</td>
<td>316 Ti</td>
<td>520 ÷ 670</td>
<td>220</td>
<td>24</td>
</tr>
</tbody>
</table>

1. valid for Mo > 2.5 %

1.3 Higher strength hull structural steel is grouped into the following grades, which differ from each other in their toughness properties:

- GL–A 32/36/40
- GL–D 32/36/40
- GL–E 32/36/40
- GL–F 32/36/40

For further advice regarding structural steel, material selection and material classes refer to GL Rules for Yachts ≥ 24 m (I-3-2), Section 2, B.2.3.

1.4 Forged steel and cast steel

Forged steel and cast steel for stem, stern frame, rudder post, etc. is to comply with the GL Rules for Metallic Materials (II-1). The tensile strength of forged steel and of cast steel is not to be less than 400 N/mm².

1.5 Austenitic steels

1.5.1 Stainless steels with a pitting resistance equivalent $W (W = \% Cr + 3.3 \cdot \% Mo)$ exceeding 25 are suitable for sea water without special corrosion protection, see Table 2.2.

1.5.2 Where austenitic steels are applied having a ratio $\frac{R_{p0.2}}{R_m} \leq 0.5$

on special approval the 1 % proof stress $R_{p1.0}$ may be used for scantling purposes instead of the 0.2 % proof stress $R_{p0.2}$.

C. Aluminium Alloys

The following information is based on the GL Rules for Non-Ferrous Metals (II-1-3), Section 1 with the aim of summarizing aspects applicable for the design of Yachts.

1. General

1.1 The following requirements are applicable to products made from wrought aluminium alloys having a product thickness of 3 to 50 mm inclusive. Requirements applicable to products having thicknesses outside this range are to be specially agreed with GL.

1.2 Alloys and material conditions which differ from the specified requirements given below, but which conform to national standards or the manufacturer’s material specifications may be used.

1.3 Alloy designations and material conditions specified herein comply with the designations of the Aluminium Association. With regard to the definition of the material conditions European standard EN 515 is applicable.

2. General characteristics of products

2.1 The products must have a smooth surface compatible with the method of manufacture and must be free of defects liable to impair further manufacturing processes or the proposed application of the products, e.g. cracks, laps, appreciable inclusions of extraneous substances and major mechanical damage.
3. Aluminium alloys without post treatment for hardening

3.1 Aluminium alloys of 5000 series in 0 condition are used for plates, strips and rolled sections. A representative list is defined in Table 2.3. This list as well as the list of Table 2.4, is not exhaustive. Other aluminium alloys may be considered provided the specification (manufacture, chemical composition, temper, mechanical properties, welding, etc.) and the scope of application is submitted to GL and accepted.

3.2 Unless otherwise specified, the Young's modulus of aluminium alloys is equal to 70 000 N/mm² and the Poisson's ratio equal to 0.33.

Table 2.3 Material condition and strength properties of plates and strips made of wrought aluminium alloys (with thickness t = 3.0 to 50 mm)

<table>
<thead>
<tr>
<th>Alloy number</th>
<th>Material condition</th>
<th>$R_{p0,2}$ min. [N/mm²]</th>
<th>$R_{m}$ [N/mm²]</th>
<th>Material factor $k_{Al}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL-AW-5083 (AlMg4,5Mn0,7)</td>
<td>0/H111/H112</td>
<td>125</td>
<td>275 – 350</td>
<td>1,59 – 1,34</td>
</tr>
<tr>
<td></td>
<td>H116</td>
<td>215</td>
<td>$\geq$ 305</td>
<td>1,22</td>
</tr>
<tr>
<td></td>
<td>H32</td>
<td>215</td>
<td>305 – 380</td>
<td>1,22 – 1,07</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>125</td>
<td>275</td>
<td>1,59</td>
</tr>
<tr>
<td>GL-AW-5086 (AlMg4)</td>
<td>0/H111/H112</td>
<td>100</td>
<td>240 – 310</td>
<td>1,87 – 1,55</td>
</tr>
<tr>
<td></td>
<td>H116</td>
<td>195</td>
<td>$\geq$ 275</td>
<td>1,35</td>
</tr>
<tr>
<td></td>
<td>H32</td>
<td>185</td>
<td>275 – 335</td>
<td>1,38 – 1,22</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>100</td>
<td>240 – 310</td>
<td>1,87 – 1,55</td>
</tr>
<tr>
<td>GL-AW-5754 (AlMg3)</td>
<td>0/H111/H112</td>
<td>80</td>
<td>190 – 240</td>
<td>2,35 – 1,98</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>80</td>
<td>190 – 240</td>
<td></td>
</tr>
<tr>
<td>EN-AW-5059 (AlMgMn0,8ZnZr)</td>
<td>0/H111</td>
<td>$\geq$ 160</td>
<td>$\geq$ 330</td>
<td>1,30</td>
</tr>
<tr>
<td></td>
<td>H116</td>
<td>$\geq$ 260</td>
<td>$\geq$ 360</td>
<td>1,02</td>
</tr>
<tr>
<td></td>
<td>H321</td>
<td>$\geq$ 260</td>
<td>$\geq$ 360</td>
<td>1,38</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>$\geq$ 160</td>
<td>$\geq$ 300</td>
<td></td>
</tr>
</tbody>
</table>

1 The strength properties are applicable to both longitudinal and transverse specimens.

Table 2.4 Material condition and strength properties of extruded sections, bars and pipes made of wrought aluminium alloys (with thickness t = 3.0 to 50 mm)

<table>
<thead>
<tr>
<th>Alloy number</th>
<th>Material condition</th>
<th>$R_{p0,2}$ min. [N/mm²]</th>
<th>$R_{m}$ [N/mm²]</th>
<th>Material factor $k_{Al}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL-AW-5083 (AlMg4,5Mn0,7)</td>
<td>0/H111</td>
<td>110</td>
<td>270 – 350</td>
<td>1,67 – 1,38</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>125</td>
<td>275</td>
<td>1,59</td>
</tr>
<tr>
<td>GL-AW-5086 (AlMg4)</td>
<td>0/H111</td>
<td>95</td>
<td>240 – 350</td>
<td>1,9 – 1,43</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>100</td>
<td>240</td>
<td>1,87</td>
</tr>
<tr>
<td>GL-AW-6005A (AISiMg(A))</td>
<td>T5/T6</td>
<td>215</td>
<td>$\geq$ 260</td>
<td>1,34</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>115</td>
<td>165</td>
<td>2,27</td>
</tr>
<tr>
<td>GL-AW-6061 (AISi1SiCu)</td>
<td>T5/T6</td>
<td>240</td>
<td>$\geq$ 260</td>
<td>1,27</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>115</td>
<td>155</td>
<td>2,35</td>
</tr>
<tr>
<td>GL-AW-6082 (AISi1MgMn)</td>
<td>T5/T6</td>
<td>260</td>
<td>$\geq$ 310</td>
<td>1,11</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td>125</td>
<td>185</td>
<td>2,05</td>
</tr>
</tbody>
</table>

1 The strength properties are applicable to both longitudinal and transverse specimens.
4. **Hardened aluminium alloys**

4.1 Aluminium alloys can be hardened by work hardening (Series 5000 other than condition 0 or H111) or by heat treatment (series 6000).

4.2 These types of aluminium alloys are used for extruded section, bars and pipes. A representative selection is defined in Table 2.4.

5. **Material selection**

5.1 The choice of aluminium alloys according to Table 2.4 is mainly recommendable for extrusions and where no excessive welding will be necessary. Otherwise only the mechanical characteristics of 0 or H111 conditions can be taken into account. Higher mechanical characteristics to be used must be duly justified.

5.2 In case of structures subjected to low service temperatures or intended for other particular applications, the alloys to be employed are to be defined in each separate case by GL, which will state the acceptability requirements and conditions.

5.3 For forgings and castings to be applied, requirements for chemical composition and mechanical properties are to be defined in each separate case by GL.

6. **Material factor**

The material factor $k$ for aluminium alloys is to be determined according to:

$$k_{Al} = \frac{635}{R_{p0.2} + R_m}$$

- $R_{p0.2} = 0.2\%$ proof stress of the aluminium alloy [N/mm$^2$]
- $R_m = $ tensile strength of the aluminium alloy [N/mm$^2$]

For welded connections the respective values in welded condition are to be taken. Where these figures are not available, the respective values for the soft-annealed condition are to be used.

7. **Influence of welding on mechanical characteristics**

7.1 Aluminium alloys of series 5000 in 0 condition (annealed) or in H111 condition (annealed flattened) are not subject to a drop in mechanical strength in the welded areas. But welding heat input lowers the mechanical strength of alloys of series 5000 with other conditions and of that of series 6000, which are hardened by heat treatment.

7.2 For heat-affected welding zones the mechanical characteristics of series 5000 to be considered are, normally, those of condition 0 or H111. Higher mechanical characteristics may be taken into account, provided they are duly justified.

7.3 For heat-affected zones the mechanical characteristics of series 6000 to be considered are, normally, to be indicated by the supplier.

7.4 The heat-affected zone may be taken to extend 25 mm on each side of the weld axis.

D. **Welding**

1. **General**

For welding the requirements according to GL Rules for Welding (II-3) serve as recommendation. Apart, the recommendations below are to be considered.

2. **Responsibility**

It is the responsibility of the builder to ensure that the manufacturing procedures, processes and sequences are in compliance with approved plans and sound working practice. For this purpose, the builder is to have its own quality management system.

3. **General material characteristics**

3.1 During the design stage welded joints are to be planned such as to be accessible during fabrication, to be located in the best possible position for welding and to permit the proper welding sequence to be followed.

3.2 Both the welded joints and the sequence of welding involved are to be so planned as to enable residual welding stresses to be kept to a minimum in order that no excessive deformation occurs. Welded joints should not be over dimensioned.

3.3 When planning welded joints, it must first be established that the type and grade of weld envisaged, such as full root weld penetration in the case of HV or DHV (K) weld seams, can in fact be perfectly executed under the conditions set by the limitations of the manufacturing process involved. If this is not the case, a simpler type of weld seam shall be selected and its possibly lower load bearing capacity taken into account when dimensioning the component.

3.4 Highly stressed welded joints, which therefore, are generally subject to examination, are to be so designed that the most suitable method of testing for faults can be used (radiography, ultrasonic, surface crack testing methods) in order that a reliable examination may be carried out.

3.5 Special characteristics peculiar to the material, such as the lower strength values of rolled material in the thickness direction or the softening of cold...
worked aluminium alloys as a result of welding, are factors which have to be taken into account when designing welded joints.

4. General design principles welding

The following design principles shall be applied:

- transfer of welding seams to low stress areas, like the neutral axis of a girder by using extruded sections for the upper and lower flange
- location of welding seams in such a way, that the thermal load from welding will be led to a far extent to extrusion profiles with big wall thicknesses
- edge preparation, alignment of joints are to be appropriate to the type of joint and welding position, and comply with GL Rule requirements for the welding procedures adopted
- for correct execution of welded joints, sufficient accessibility is necessary, depending on the welding process adopted and the welding position
- unfavorable welding positions have to be avoided

E. Corrosion Protection

1. General

For corrosion protection the GL Guidelines for Corrosion Protection and Coating Systems (VI-10-2) serve as recommendation. Apart, the recommendations below serve as a summary.

2. Shop primers

Shop primers are used to provide protection of the steel parts during storage, transport and work processes.

Customarily, coatings with a thickness of 15 to 20 µm are applied. This should provide corrosion protection for a period of approx. 6 months.

3. Hollow spaces

Hollow spaces, such as those in closed box girders, tube supports and the like, which either can be shown to be air tight or are accepted as such from normal shipbuilding experience, need not have their internal surfaces protected. During assembling, however such hollow spaces must be kept clean and dry.

4. Combination of materials

Preventive measures are to be taken to avoid contact corrosion associated with the combination of dissimilar metals with different potentials in an electrolyte solution, such as seawater. The resulting differences in potential greatly increase the susceptibility to corrosion and must therefore be given special attention. Where possible, such welds are to be positioned in locations less subject to the risk of corrosion (such as the outside of tanks) or special counter-measures are to be taken. These counter-measures include the selection of appropriate materials and furthermore steps such as suitable insulation, an effective coating and the application of cathodic protection.

4.1 Heterogeneous assemblies of steel and aluminium alloys

Connections between aluminium alloy and steel parts, if any, are to be protected against corrosion by means of coatings applied by suitable procedures agreed by GL. In any case, any direct contact between steel and aluminium alloy is to be avoided (e.g. by means of zinc or cadmium plating of the steel parts and application of a suitable coating on the corresponding light alloy parts).

5. Corrosion protection of ballast water tanks

All seawater ballast tanks having boundaries formed by the vessel’s side shell (bottom, outside plating, deck) must be provided with a corrosion protection system consisting of coating and cathodic protection.

6. Corrosion protection of the underwater hull

6.1 Coatings based on epoxy, polyurethane and polyvinyl chloride are considered suitable.

6.2 The coating manufacturer’s instructions with regard to surface preparation as well as application conditions and processing must be observed.

6.3 The coating system without antifouling shall:

- have a minimum dry film thickness of 250 µm
- provide cathodic protection in accordance with recognized standards
- be suitable for being cleaned underwater by mechanical means

6.4 The cathodic protection can be provided by means of sacrificial anodes, or by impressed current systems. Under normal conditions for steel, a protection current density of at least 10 mA/m² must be ensured. Hulls or components made of aluminium and aluminium alloys, which are permanently immersed in seawater need to be protected by sacrificial anodes. For hull structures or components of zinc-free aluminium materials which are permanently submerged in seawater, cathodic protection with a protective potential of less than - 0.55 V by sacrificial anodes is required. A cathodic protection is especially needed, if galvanic corrosion is to be expected.
due to a bimetallic couple between the submerged aluminium alloy structure and other parts, e.g. propulsion components such as stainless steel propeller shafts, bronze propellers or steel hydrojets. Therefore metallic connection between aluminium alloy structures and other metals should be avoided.

6.5 In the case of impressed current systems, overprotection due to inadequately low potential is to be avoided. A screen (dielectric shield) is to be provided in the immediate vicinity of the impressed current anodes.

7. Corrosion protection of austenitic stainless steels

Stainless steels and stainless steel castings exhibit a passive surface state in seawater. Accordingly, coating these types of steel is only recommended under special conditions. In general uncoated stainless steels are not protected by cathodic corrosion protection if they are suitable for withstanding the corrosion stress. Coated stainless steels must be cathodically protected in the submerged zone.

F. Cold-molded Wood and Bonding

1. General

The following GL Rules serve as guide in addition to the below:
- Wooden Materials (II-2-2)
- Yachts ≥ 24 m (I-3-2), Section 2, B.8.

2. Wood

2.1 Any of the timbers suitable for boat building may be used.

2.2 Timber envisaged for use in this type of construction is to be cut in such a way that the inclination of the annual rings is not less than 30°, i.e. the angle between the chord of the flattest annual ring, and the face of a lamella or strip of veneer must not be less than 30°. The fibers shall be oriented parallel to the edge of a lamella, if possible. Veneers for making plating may be sliced or sawn.

2.3 Glues and adhesives

Only adhesives and glues accepted by GL may be used.

3. Wood and joining of wooden materials

The following requirements are an excerpt of the GL Rules for Wooden Materials (II-2-2) with the aim of summarizing all aspects directly necessary for the design of yachts.

4. Timber selection according to the field of application

Only proven boatbuilding wood shall be used for all timber components exposed to water and weather, i.e. timber with good resistance to water and weather, fungal attack and insect infestation, as well as with good mechanical properties that are also suitable for the particular application. Furthermore, it shall have low swelling and shrinkage properties. For components not exposed to water or weather, and not requiring strength, timber of lower durability may be used.

4.1 Quality

The timber used in boatbuilding shall be long grained and of best quality, i.e. free from sap, shakes objectionable knots and other defects. Twisted-grown or rough saw cut shall not be used.

4.2 Drying

The timber used shall be well seasoned and sufficiently dried in a suitable drying kiln. In case of forced drying, the residual moisture content shall not be more than 10 %. When processing, this content shall not exceed 15 % as a result of hygroscopic behaviour.

5. Solid wood

5.1 Radially sawn timber shall mainly be used for boatbuilding. The angle of the annual rings to the lower sawn edge shall not be less than 45°.

5.2 Table 2.5 shows the number of different types of timber and their most important properties, as well as tensile, compressive and bending strength. Since these properties can vary in the case of timber of the same type, or even within the same trunk, no absolute values are indicated in the table, but rather characteristic values. The timber listed is divided into durability groups from I to V. The timber used in boatbuilding shall, if exposed to the weather or used for the primary structural components of a boat, belong to at least durability group III.

5.3 In place of the timber listed in Table 2.5, other types can be used if the durability and the technological values are verified and are equivalent. The manufacturer shall always be responsible for the correct selection of the quality and type of wood.

5.4 The safety factors used in the strength calculation shall be agreed in each case with GL.
6. Boatbuilding plywood

6.1 General

6.1.1 All plywood components exposed to water and weather, or used in primary structural components (such as the deck, shell and bulkheads), shall be produced from boatbuilding plywood that has been tested according to GL Rules.

6.1.2 The boatbuilding plywood consists of at least three veneers bonded crosswise together by means of curable synthetic-resin adhesives. The resistance of these adhesives to water and weather shall be demonstrated by long-term and outdoor testing.

6.1.3 As plywood can also be destroyed in specific adverse conditions by animal or plant pests, timber shall be used which offers a natural resistance.

6.2 Plywood set-up

The selection of timber and the structure of the panels (number of veneer layers) shall be appropriate for the field of application. Depending on the application, strong, durable timber - e.g. makoré and the hard, durable mahogany types of strength group F1 (see Table 2.6) - with several thin inner layers of veneer shall be selected for load carrying components subject to high stresses. On the other hand, plywood panels of lighter, less long and less durable timber of strength group F2 e.g. khaya, mahogany, okumé - with thicker and fewer inner layers of veneer and good surface protection are suitable for linings.

6.3 Veneer joints

The veneer joints shall be sealed perfectly and shall bond the veneers to each other by butt joints. The joints shall be glued on a suitable joint bonding machine. Sealed joints between all layers are a precondition for boatbuilding plywood.

6.4 Strength groups

6.4.1 With regard to their suitability for the production of boatbuilding plywood, the types of timber listed in Table 2.6 are currently approved. The timber is subdivided into two strength groups. Also shown is the natural durability and weathering resistance of the mentioned types of timber.

6.4.2 Other types of wood may only be used for making plywood panels upon agreement with GL. The manufacturer shall always remain responsible for the correct selection of quality and type of wood.

6.5 Wood protection

6.5.1 Timber

All timber (with exception of the timber durability group I, Table 2.6) shall be protected by several coats of suitable protective paint, or by means of impregnation with a proven wood preservative, against fungi and insect infestation. Impregnation is the preferred method for interior surfaces of the yacht's components which are exposed to water or weather (e.g. hull, deck, and superstructure) and which have received a coat of paint impervious to vapour pressure.

6.5.2 Plywood

All plywood parts shall be protected by several coats of paint or varnish. Special attention shall be paid to plywood edges and drill-holes by pre-treating them with recognized and proven edge protection coatings.
## Table 2.5  Timber durability groups and characteristic values in accordance with DIN 68364

<table>
<thead>
<tr>
<th>Timber type</th>
<th>Durability group</th>
<th>Density [g/cm³]</th>
<th>Mean breaking strengths</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I – V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coniferous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine</td>
<td>III – IV</td>
<td>0.52</td>
<td>100</td>
<td>45</td>
</tr>
<tr>
<td>Oregon pine</td>
<td>III</td>
<td>0.54</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Larch</td>
<td>III</td>
<td>0.59</td>
<td>105</td>
<td>48</td>
</tr>
<tr>
<td>Deciduous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khaya mahogany</td>
<td>III</td>
<td>0.5</td>
<td>75</td>
<td>43</td>
</tr>
<tr>
<td>True mahogany</td>
<td>II</td>
<td>0.54</td>
<td>100</td>
<td>45</td>
</tr>
<tr>
<td>Sapele mahogany</td>
<td>III</td>
<td>0.64</td>
<td>85</td>
<td>57</td>
</tr>
<tr>
<td>Utile</td>
<td>II</td>
<td>0.59</td>
<td>100</td>
<td>58</td>
</tr>
<tr>
<td>Meranti, red</td>
<td>III</td>
<td>0.59</td>
<td>129</td>
<td>53</td>
</tr>
<tr>
<td>Iroko</td>
<td>I – II</td>
<td>0.63</td>
<td>79</td>
<td>55</td>
</tr>
<tr>
<td>Makore</td>
<td>I – II</td>
<td>0.66</td>
<td>85</td>
<td>53</td>
</tr>
<tr>
<td>Oak</td>
<td>II</td>
<td>0.67</td>
<td>110</td>
<td>52</td>
</tr>
<tr>
<td>Teak</td>
<td>I</td>
<td>0.69</td>
<td>115</td>
<td>58</td>
</tr>
<tr>
<td>Yang</td>
<td>III</td>
<td>0.76</td>
<td>140</td>
<td>70</td>
</tr>
</tbody>
</table>

### Durability groups:
- I = very good
- II = good
- III = average
- IV = moderate
- V = poor

## Table 2.6  Plywood strength and durability groups

<table>
<thead>
<tr>
<th>Timber type</th>
<th>Botanical name</th>
<th>Durability group</th>
<th>Density Approx. [g/cm³]</th>
<th>Mean tensile strength of plywood Longitudinal Transverse</th>
<th>Bending [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>I – V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength group F1 (for loadbearing components)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teak</td>
<td>Tectona grandis</td>
<td>I</td>
<td>0.64</td>
<td>≥ 40</td>
<td>≥ 30</td>
</tr>
<tr>
<td>Makoré</td>
<td>Dumoria hekelii</td>
<td>I</td>
<td>0.62</td>
<td>≥ 40</td>
<td>≥ 30</td>
</tr>
<tr>
<td>Douka</td>
<td>Dumoria africana</td>
<td>I</td>
<td>0.62</td>
<td>≥ 40</td>
<td>≥ 30</td>
</tr>
<tr>
<td>Utile</td>
<td>Entandro-phragma utile</td>
<td>II</td>
<td>0.57</td>
<td>≥ 40</td>
<td>≥ 30</td>
</tr>
<tr>
<td>Sapele mahogany</td>
<td>Entandro-phragma cylindricum</td>
<td>III</td>
<td>0.59</td>
<td>≥ 40</td>
<td>≥ 30</td>
</tr>
<tr>
<td>Oak</td>
<td>Querus robur</td>
<td>II</td>
<td>0.63</td>
<td>≥ 40</td>
<td>≥ 30</td>
</tr>
<tr>
<td>Strength group F2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American mahogany</td>
<td>Swietenia macrophylla</td>
<td>II</td>
<td>0.49</td>
<td>&lt; 40</td>
<td>&lt; 30</td>
</tr>
<tr>
<td>African mahogany</td>
<td>Khaya ivorensis</td>
<td>II – III</td>
<td>0.45</td>
<td>&lt; 40</td>
<td>&lt; 30</td>
</tr>
<tr>
<td>Okouné (Gaboon)</td>
<td>Aucoumea klaineana</td>
<td>IV - V</td>
<td>0.41</td>
<td>&lt; 40</td>
<td>&lt; 30</td>
</tr>
</tbody>
</table>

### Durability groups:
- I = very good
- II = good
- III = average
- IV = moderate
- V = poor
Section 3

Design Loads

A. General

1. As per the definition of these guidelines, the yacht’s structure is exposed to quasi static and quasi dynamic sea loads and/or other operational loads. These loads are called “design loads”. The design loads in general are to be applied at the following effective locations:

– for panels: lower edge of panel
– for structural members: centre of the area supported by the element

Note

Values derived must not necessarily be corrected for units, insert as defined.

B. Lateral Design Pressures

1. Sea pressures on hull

1.1 The pressure $p_H$ [kN/m²] on the yacht's hull is to be determined as follows:

$$p_H = 10 \cdot T_H \left( 1 - \frac{z}{H} \right) + c_p \cdot c_L \cdot L \left( 1 + \frac{v_0}{3 \cdot \sqrt{L}} \right) \cos \left( \frac{\alpha}{1.5} \right)$$

$v_0$ = yacht’s speed [kn] see Section 1, C.1.1

$c_p$ = panel size factor as a function of $f$, see Fig. 3.3, approximated by:

$$c_p = 0.54 \cdot f^2 - 1.29 \cdot f + \ell$$

for panels:

$$f = \frac{a - 250}{55 \cdot L + 550}$$

$a$ = panel’s short span respectively load span of stiffener [mm], for the purpose of determining sea pressures not to be taken < 250 mm or > 1300 mm

for stiffeners and girders:

$$f = \frac{\ell - 250}{55 \cdot L + 550}$$

$\ell$ = length of girders or stiffeners length between supports [mm], for the purpose of determining sea pressures not to be taken < 250 mm or > 1300 mm

$c_L$ = hull longitudinal distribution factor see Fig. 3.4

for $\frac{x}{L} < 0$:

$$c_L = 0.80 \quad \text{for} \quad L = 24 \text{ m}$$

$$c_L = 0.60 \quad \text{for} \quad L = 48 \text{ m}$$

for $0 \leq \frac{x}{L} \leq 0.65$:

$$c_L = 0.80 + 0.615 \cdot \frac{x}{L} \quad \text{for} \quad L = 24 \text{ m}$$

$$c_L = 0.60 + 0.538 \cdot \frac{x}{L} \quad \text{for} \quad L = 48 \text{ m}$$

for $\frac{x}{L} \geq 0.65$:

$$c_L = 1.20 \quad \text{for} \quad L = 24 \text{ m}$$

$$c_L = 0.95 \quad \text{for} \quad L = 48 \text{ m}$$

$z$ = vertical distance between the load point and the molded base line [m],

$\alpha = \beta - 20^\circ$, $\alpha$ not smaller than $0^\circ$

$\beta$ = deadrise angle at load point

1.2 In any case the load $p_H$ shall not be smaller than:

$$p_{H\text{min}} = 10 \cdot H \quad [\text{kN/m}^2]$$

for the area of the hull below the full displacement waterline

and:

$$p_{H\text{min}} = 5 \cdot H \quad [\text{kN/m}^2]$$

for the area of the hull above the full displacement waterline

2. Impact pressures on forward hull bottom

2.1 Slamming on forward hull bottom is particularly assumed to occur when the hull is of low canoe body draft and shows large areas of low local deadrise. The below pressure values $p_{sl}$ apply if they are
larger than the above defined sea pressures. They have to be applied to the hull bottom in an area where the local deadrise is lower than 50° in upright floatation or below DWL, whichever gives a greater area.

2.2 The pressure $p_{sl}$ [kN/m$^2$] on the yacht's hull is to be determined as follows:

$$P_{sl} = 3 \cdot K_2 \cdot K_3 \cdot K_{WD} \cdot v_0 \cdot v_{sl}$$ [kN/m$^2$]

$v_0$ = yacht’s speed [kn] see Section 1, C.1.1
$v_{sl}$ = relative impact velocity [m/s]

$$= 4 \cdot \frac{H_S}{\sqrt{L}} + 1$$

$H_S$ = relevant critical significant wave height [m]

$K_2$ = factor accounting for impact area

$$= 0.455 - 0.35 \cdot \left(\frac{u}{0.75} - 1.7\right)$$

$u = \frac{H_S}{\sqrt{L}}$

$K_3$ = factor accounting for shape and deadrise of hull:

$$= 100 - \frac{\alpha}{70}$$

$\alpha$ = mean local deadrise of slamming area, may not be taken smaller than 30°. Slamming is applicable up to $\alpha = 50°$

$K_{WD}$ = longitudinal bottom slamming distribution factor, see Fig. 3.1

$$= 0 \quad \text{aft of 0.5 } L$$

$$= 10 \cdot \frac{x}{L} - 5 \quad \text{between 0.5 } L \text{ and 0.6 } L$$

$$= 1.0 \quad \text{forward of 0.6 } L$$

3. **Loads on weather decks**

The design pressure on weather decks is to be determined according to the following formula:

$$p_{D, min} = 6.0 \text{ kN/m}^2$$

$z$ = local height of weather deck above DWL [m]
$c_D$ = deck longitudinal distribution factor

$$= 1.20 \quad \text{for } \frac{x}{L} < 0.05$$

$$= 1.25 - \frac{x}{L} \quad \text{for } 0.05 \leq \frac{x}{L} \leq 0.25$$

$$= 1.00 \quad \text{for } 0.25 \leq \frac{x}{L} \leq 0.70$$

$$= 2.5 \frac{x}{L} - 0.75 \quad \text{for } 0.70 \leq \frac{x}{L} \leq 0.90$$

$$= 1.50 \quad \text{for } \frac{x}{L} \geq 0.90$$

4. **Loads on superstructures and deckhouses**

4.1 **Load on walls**

4.1.1 **Front walls**

The design load is:

$$p_{AFW} = 1.5 \cdot p_D \text{ [kN/m}^2]$$

4.1.2 **Side walls**

The design load is:

$$p_{ASW} = 1.2 \cdot p_D \text{ [kN/m}^2]$$

4.1.3 **Aftwalls**

The design load is:

$$p_{AAW} = 0.8 \cdot p_D \text{ [kN/m}^2]$$
4.2 Loads on superstructure decks

The load on decks of superstructures and deckhouses is based on the load on the weather deck according to 3. and is defined by the following formula:

\[ p_{DA} = p_D \cdot n \quad [\text{kN/m}^2] \]

\[ p_{DA, \text{min}} = 4.0 \text{ kN/m}^2 \]

\[ n = 1 - \frac{z - (H - T_H)}{10} \]

\[ z = \text{vertical distance of superstructure deck above DWL [m]} \]

5. Loads on accommodation decks

The load on accommodation decks can be assumed as:

\[ p_L = p_C \cdot c_D \quad [\text{kN/m}^2] \]

\[ p_C = \text{to be defined by the designer in connection with the owner's specification} \]

\[ p_{C, \text{min}} = 3.5 \text{ kN/m}^2 \]

\[ c_D = \text{longitudinal distribution factor according to Fig. 3.5} \]

6. Loads on bulkheads

Bulkheads are subject to in-plane loading by hull and deck lateral design pressures, global shear and torque and local loads and have to cope with these loadings not exceeding allowable stresses and strains. Besides, buckling of bulkheads shall be considered.

In the following paragraphs, lateral pressure loads for bulkheads are defined; relevant in-plane sea loads were defined in paragraphs 2., 3., and 4.

6.1 Collision bulkhead

The design load is:

\[ p_{BH} = 11.5 \cdot z_{BH} \quad [\text{kN/m}^2] \]

\[ z_{BH} = \text{vertical distance from the load centre to the top of the bulkhead in [m]} \]

6.2 Other watertight bulkheads

The design load is:

\[ p_{BH} = 10.0 \cdot z_{BH} \quad [\text{kN/m}^2] \]

7. Loads on tank structures

For outer boundary plating the design load is:

\[ p_T = 10.0 \cdot z_T \quad [\text{kN/m}^2] \]

\[ z_T = \text{vertical distance from the load centre to the top of the tank overflow in [m]} \]

\[ = \text{not to be taken less than 2.0 m} \]

For tank baffles: Without further proof, a default design pressure of 20 kN/m² is to be adopted. GL can assist with separate guidance for more refined set of pressures upon request.

Fig. 3.2 Characteristic parameters for panels of the yacht’s hull

Fig. 3.3 Panel size factor \( c_p \)

Fig. 3.4 Hull longitudinal distribution factor \( c_L \)
C. Design Loads for Keel and Keel Attachments

1. General

The structure of the ballast keel and also the yacht’s bottom and floor structure in way of the keel attachment must be able to withstand the structural loadings described below. All relevant structural components of such an assembly have to be assessed, at multiple locations, if necessary (e.g. keel root, keel box, half span of fin or bulb attachment).

2. Design loads

The following design loads are for fixed keels, lifting keels and canting keels. In general, the below load cases apply to lifting keels only in fully-up (fixed) or fully-down (fixed) positions. For lifting and lowering sequences structures need to be sound under moderate motions of the vessel, lifting and lowering must only performed in relatively calm water. Lifting and lowering in shallow water may only be performed at zero speed over ground. A canting keel will have to undergo assessment with the keel canted in different angles. The following cases may be assessed separately for the purpose of deriving scantling requirements.

2.1 LC1 keel load “heeling”

\[ F_1 = 2 \cdot \{1.0 \cdot \text{mk}_1 \cdot g \cdot c_d \} \]

\[ c_d = \text{dynamic offset factor} \]

\[ = 1.0 \text{ for fixed keel or lifting keels with the boat heeled to } 90^\circ \]

\[ = 1.0 \text{ for lifting keels with keel in fully-up position, when not used for sailing, with boat heeled to } 30^\circ \]

\[ = 1.4 \text{ for canting keels with keel at maximum canting angle and boat heeled to } 30^\circ \]

\[ \text{mk}_1 = \text{mass of keel (in general: fin and bulb) relevant to structural assessment} \]

\[ g = \text{acceleration of gravity} \]

\[ = 9.81 \text{ m/s}^2 \]

For the determination of structural response on keel design forces \( F_1 \), relevant values of \( \text{mk}_1 \), occurring at pertinent center of gravity in the direction of gravity, shall be taken to assess structural aspects at different locations, e.g. keel root, keel box, half span of fin or bulb attachment.

2.2 LC2 keel load “pounding”

\[ F_{2(z)} = 1.1 \cdot g \cdot (\Delta - \text{mk}_1) \]

\[ \Delta = \text{Displacement of vessel fully loaded} \]

For the determination of structural response, the vertical design force is acting upwards on the bulb bottom, in line with total keel center of gravity with the boat upright; canting keels with keel in 0° cant position.

2.3 LC3 keel load “grounding”

\[ F_{3(x)} = -1.5 \cdot g \cdot (\Delta - \text{mk}_2) \]

\[ F_{3(y)} = 0.2 \cdot F_{3(x)} \]

\[ \text{mk}_2 = \text{concentrated mass of keel in way of grounding contact (in general: bulb)} \]

For the determination of structural response, the design forces are to be applied to the foremost tip of the keel bulb with boat in upright situation and canting keel in 0° and max. canting angle position. x and y coordinates are in boat-fixed coordinate system.

3. Keel and keel attachment scantling determination

3.1 Metal construction

Permissible material stresses for components of keel and associated structures subject to the loads as specified in 2. are defined in Section 5, C.7.

3.2 Fiber reinforced composites

Permissible material strains and safety factors for components of keel and associated structures subject to the loads as specified in 2. are defined in Section 4, C.8., where these permissible strains may be 1,4 times higher and safety factors 1,4 times lower for load case 3.

D. Rudder Design Loads

1. General

This paragraph is 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 com-
ponents 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.

For (forward) canard rudders, a separate load assessment has to be carried out, possibly including sea loads.

For twin rudders, the following applies for each rudder.

For any other type rudders, consult GL Rules for Yachts ≥ 24 m (I-3-2), Section 2, J.

2. **Rudder loads**

2.1 **Rudder hydrodynamic side force**

The resultant hydrodynamic side force of a rudder for the purpose of assessing its scantlings is to be calculated using the following formula:

\[
C_R = 136 \cdot c_L \cdot v_0^2 \cdot A \quad [N]
\]

\(A\) = lateral area of rudder \([m^2]\)

\(v_0\) = design speed according to Section 1, C.1.1 \([kn]\)

\(c_L\) = maximum lift coefficient

\[
= \frac{0.11}{\left(1 + \frac{2}{AR_e}\right)} \cdot a_0
\]

\(a_0\) = maximum angle of attack before stall \([°]\)

\(= 13°\) may be used in absence of value

\(AR_e\) = effective aspect ratio

\[
= 2 \frac{b^2}{A}
\]

\(b\) = see Fig. 3.6

2.2 **Torsional moment**

The maximum torque on rudder blade and rudder shaft is to be calculated using the following formula:

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

Where:

\(r\) = distance between CoE and rudder shaft axis

\(= x_c - f\) if the axis of the rudder lies within the rudder

\(= x_c + f\) if the axis of the rudder lies forward of the rudder

\(x_c, f\) and \(r_{min}\) as in Fig. 3.6

2.3 **Rudder bearings**

The rudder force \(C_R\) shall be shared between the individual bearings according to the vertical position of the rudder’s geometric centre of effort which can be assumed to be located at the same height as the geometrical centre of the blade.
The reaction loads on the bearings are to be calculated as follows:

Upper bearing: \[ B_2 = \frac{C_R \cdot t}{a} \]

Lower bearing: \[ B_1 = B_2 + C_R \]

The same forces are to be used to design foundations or hull and deck reinforcements.

Rudder bearings shall provide sufficient rotational freedom to allow for a bent rudder shaft to avoid pertinent constraints on the bearing, the shaft and the affected hull structure.

4. **Rudder scantlings**

Rudder force and Rudder torque as per 2.1 and 2.2 have to be used to design rudder stock and rudder blade scantlings. The rudder force shall be used as a lateral pressure force together with the relevant CoA/CoE to design the rudder and the stock at characteristic locations. The rudder torque at different locations shall be the rudder and the stock at characteristic locations. The rudder torque at different locations shall be derived using the local resultant pressure force, CoE and a torque lever as per definition from 2.2.

For fiber composite design, allowable strains in shaft and blade may not exceed limits as per definition in Section 4, C.8.

Metal parts of the rudder shall be treated in accordance with allowable stresses defined in Section 5, C.7.

5. **Rudder equipment**

The rudder quadrant mounted on the shaft has to transmit torque without weakening the rudder shaft.

An emergency tiller is recommended being designed to cope with a rudder shaft torque resulting from 70 % of the design speed \( v_0 \).

E. **Global Loads**

1. **General**

Global loads are considered loads acting on the global hull girder without the consideration of local load introduction. For slender monohulls such as racing yachts, relevant global loads are global vertical shear force \( F_z \) and global vertical bending moment \( M_y \). Others are relevant to a lower degree and/or for unusual configurations.

1.1 Global loads are considered to arise through sea loads and through the rig attachments.

2. **Load cases**

For racing yachts it is considered sufficient to superimpose two loadcases:

2.1 **Rig loads from headstay/backstay.**

The maximum working loads of the different headstays shall be used to create a global shear force and bending moment forward of the mast frame, reducing to zero at the stern aft of the mast frame. See Fig. 3.7 and Fig. 3.8.

2.2 **Pressure loads from slamming of forward hull bottom.**

Pertinent slamming pressure loads have to be determined according B.2., using a \( K_2 \) of 0.175. The pressures have to be applied across the total area designated as slamming area. This way, a shear force and bending moment distribution forward of \( 0.5 \cdot L \) is created.

Aft of \( 0.5 \cdot L \), both distributions are reflected. See Fig. 3.7 and Fig. 3.8.

3. The above load values shall be combined and used to check global hull sections at different longitudinal stations. Allowable stresses/strains defined in relevant sections are not to be exceeded. Beside the static strength analysis, a buckling analysis shall be performed to make sure that deck buckling will not be critical.
Fig. 3.7 Shear force distribution

Fig. 3.8 Bending moment distribution
Section 4
Design and Scantlings for Composite Structures

A. General

1. Scope

1.1 The following specifies requirements for the design 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. For lengths $L$ above 48 m special considerations for the extrapolation of these Rules have to be agreed with GL. The requirements apply also to hulls of cold-molded wood construction, as far as transferrable.

1.2 Different types of fibers and the multitude of fiber arrangements, as well as different core materials give rise to sophisticated laminate lay-ups of components specifically designed for the loads expected. Strength and stiffness calculations for such structures require careful analysis.

2. Information to be provided

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

2.1 Fiber and resin materials:
– resin system, specific gravity
Cured ply properties for:
– fiber areal weight
– fiber orientation
– consolidation method and fiber volume fraction
– thickness
– 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

2.2 Core materials:
– type, manufacturer
– nominal density
– thickness
– ultimate shear strength
– compressive stiffness
– shear stiffness

2.3 Laminates

For each structural component, the documentation must contain data covering:
– 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. Materials

3.1 Regarding FRP and core materials, the GL-Rules for Fibre Reinforced Plastics and Bonding (II-2-1) apply. An excerpt of these Rules is contained in Section 2, A.

3.2 The actual mechanical properties of all FRP layers and the core materials have to be submitted to GL and are to be verified by tests. The information about the properties shall also include nominal thickness of each ply, specific weight per area and fiber content.

B. Principles for Structural Design

1. General structural arrangement

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 are to be supported by transverse web frames or transverse bulkheads. Transverse frames are to 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.

1.2 Care is to be taken to ensure structural continuity and to avoid sharp corners and abrupt changes in section and shape.
Where frames, beams and stiffeners are intercostal at an intersecting member, the connections are to provide continuity of strength.

1.3 Floors are to be fitted in line with transverse webs or transverse frames. Alternatively, floors may terminate at longitudinal girders which in turn are supported by deep web rings or transverse bulkheads. Floors or equivalent stiffeners are to be fitted in the area of the engine foundations, the rudder skeg and the propeller bracket, if applicable. For sailing yachts with short ballast keels, a reinforced floor at the leading and trailing edge of the keel is to be arranged.

1.4 Yachts shall have transverse bulkheads or equivalent structures in way of mast(s) in order to achieve adequate transverse rigidity. Transverse bulkheads or deep brackets are to be provided in way of chainplates.

2. Longitudinal strength

A longitudinal strength calculation is to be carried out using the loads defined in Section 3, E.

3. Bulkheads

3.1 Number and location of watertight bulkheads should be considered in the early design phase to ensure compliance with these Rules and possibly other relevant regulations.

Bulkhead stiffeners, where required, are to be aligned with hull girders.

3.2 Collision bulkhead

The collision bulkhead shall extend watertight up to the weather deck. Steps or recesses may be permitted.

Openings in the collision bulkhead shall be watertight and permanently closed in sailing condition. Closing appliances and their number shall be reduced to the minimum, compatible with the design and proper working of the yacht.

Where pipes are penetrating the collision bulkhead, screwdown valves are to be fitted directly at the collision bulkhead. Such valves are to be operable from outside the forepeak.

3.3 Openings in watertight bulkheads

In watertight bulkheads other than collision bulkheads, watertight doors may be fitted. Watertight doors are to be sufficiently strong and of an approved design.

Openings for watertight doors in the bulkheads are to be effectively framed such as to facilitate proper fitting of the doors and to guarantee water tightness.

3.3.1 Watertight bulkhead doors and their frames are to be tested before they are fitted onboard by a head of water corresponding to the freeboard deck height or the results from damage stability calculation. Alternatively, watertight doors may be used which have been type approved in accordance with GL special acceptance procedure. After having been fitted on board, the doors are to be soap-tested for tightness and to be subject to an operational test.

3.3.2 Penetrations through watertight bulkheads

Where bulkhead fittings are penetrating watertight bulkheads, care is to be taken to maintain water tightness. For penetrations through the collision bulkhead 3.2 is to be observed.

4. Openings

Corners of all openings in strength structures are to be well rounded. If necessary, the shape of openings is to be designed to reduce stress concentrations. Structural integrity must be maintained around openings. In highly stressed areas openings should be avoided as far as possible.

5. Bottom structure

5.1 In general, continuous longitudinal girders are to be provided and shall extend as far aft and forward as practicable. A centreline girder is to be fitted for docking purposes unless sufficient strength and stiffness is already achieved by the external keel or the bottom shape.

5.2 Size and location of cut-outs in floors and girders must be appropriately designed for the occurring loads. Particularly at the ends of floors and girders sufficient shear area is required.

5.3 A floor or a girder is to be provided under each line of pillars.

5.4 In case of a double bottom, manholes must be arranged for access to all parts of the double bottom.

5.5 Where solid ballast is fitted, it is to be securely positioned. If necessary, intermediate floors may be fitted for this purpose. If a ballast keel is fitted, the bottom structure is to be reinforced due to additional loads transmitted by the keel. Special care is to be taken with the structural support of fin keel’s leading and trailing edge.

6. Engine foundation

Longitudinal girders forming the engine seatings must extend fore and aft as far as possible and are to be suitably supported by floors, transverse frames and/or brackets. In way of thrust bearing additional strengthening is to be provided.
7. Side structure and bulwarks

7.1 Longitudinal stiffeners, if fitted, shall be continuous as far as possible.

7.2 Bulwark plating is to be determined by applying the side design pressure for the relevant vertical height.

8. Tank structures

8.1 Tanks longer or wider than 0.1 L require effective internal baffles. It is recommended that the degree of perforation is no less than 5% and no more than 10%, but under no circumstances more than 50% of the unperforated section area of the tank baffle.

8.2 Fresh water tanks are to be separated from other tanks such as waste water tanks by cofferdams. The same applies to fuel tanks. Generally, also tanks such as lubricating or hydraulic oil tanks shall be separated from each other by equivalent means.

9. Deck

9.1 In case of longitudinal deck stiffeners, deck beams are to be located in way of the vertical web frames of the side shell. Structural continuity of the stiffeners is to be ensured.

9.2 In case of transverse deck stiffeners, deck beams are to be, in general, fitted at every frame, in line with side shell stiffeners.

10. Superstructures and deckhouses

10.1 Superstructure and deckhouse front and aft bulkheads are to be aligned with bulkheads, web frames or pillars in the hull or in the superstructure or deckhouse below.

10.2 Web frames or partial/wing bulkheads are to be provided to ensure transverse rigidity in large deckhouses. The strength members are to be suitably reinforced in the area of masts and other load concentrations.

10.3 Ends of superstructures and deckhouses are to be efficiently supported by bulkheads, pillars or other equivalent arrangements.

10.4 As a rule, the spacing of stiffeners on sides of superstructures and deckhouses is to be the same as those of beams on supporting decks.

10.5 Structural discontinuities and rigid points are to be avoided. Where structural elements are weakened, e.g. by openings, proper compensation is to be provided.

11. Constructional details

11.1 Changes of thickness for a single-skin laminate are to 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. The connection between a single-skin laminate and a sandwich laminate is to 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.

11.2 Laminate edges and holes are to be sealed.

11.3 In way of bolted connections and fittings, the sandwich core is to be replaced by inserts of high density foam or single-skin laminate.

12. Applicable design load

Design loads as defined in Section 3 have to be applied.

C. Scantlings

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 such as pressure loading on watertight bulkheads 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 will have to apply, 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).

Guidance Note

If not explicitly mentioned, use consistent unit variables.
2. Elasto-mechanical properties of laminated structures

2.1 Nomenclature

\( \psi \) = mass content of reinforcing material in a laminate

\( \varphi \) = volume content of reinforcement material in a laminate

\( E_{11} \) = Young’s modulus of a single ply with unidirectional fibers, parallel to fibers

\( E_{22} \) = Young’s modulus of a single ply with unidirectional fibers, perpendicular to fibers

\( \nu_{12}, \nu_{21} \) = Poisson’s ratios of a single ply

\( G_{12} \) = shear modulus of a single ply

\( \rho_f \) = specific gravity of fiber material

\( \rho_m \) = specific gravity of matrix material

\( E_{fL} \) = Young’s modulus of fiber in fiber direction

\( E_{fT} \) = Young’s modulus of fiber transverse to fiber direction

\( E_m \) = Young’s modulus of matrix

\( \nu_{12} \) = Poisson’s ratio of fiber

\( \nu_m \) = Poisson’s ratio of resin

\( G_m \) = shear modulus of the matrix

\( G_f \) = shear modulus of the fiber

\( E_x \) = Young’s modulus of a ply, multiply or laminate in x-direction of global laminate coordinate system

\( E_y \) = Young’s modulus of a ply, multiply or laminate in y-direction of global laminate coordinate system

\( G_{xy} \) = shear modulus of a ply, multiply or laminate in xy-direction of global laminate coordinate system

\( \Theta \) = angle of inclination/transformation from local ply coordinate system (1, 2 coordinates) to global laminate coordinate system (x, y coordinates), see Fig 4.1.

Laminate = is a general expression for a structural unity, a composition of structural fibers, laid down in a polymer matrix. A laminate may contain a sandwich core or other constituents for achieving certain mechanical purposes.

Layer types:

ply = In the definition of these Rules, a ply is one laminated layer containing fiber reinforcements aligned in one direction only (unidirectional) or one layer of isotropic or quasi-isotropic material (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 stitched arrangement, or as pre-preg).

Fig. 4.1  Local single ply and global laminate coordinate systems

2.2 Basic single ply analysis

2.2.1 Fiber content by volume

The fiber volume fraction of a laminate is determined by the formula:

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

The thickness \( t_{i,\text{ply}} \) of a single ply is then derived as:

\[
t_{i,\text{ply}} = m_i \cdot \left( \frac{1}{\rho_f} + \frac{1 - \psi_i}{\psi_i \cdot \rho_m} \right)
\]

\( m_i \) = single ply areal weight of fiber reinforcements

\( \psi_i \) = fiber mass fraction of single ply

2.2.2 Basic ply stiffness properties

A single unidirectional laminated ply consists of long fibers, oriented in one direction, embedded in a polymeric matrix. Typical fiber materials are E-glass, aramid or carbon. Representative material properties of fiber and matrix materials can be found in Table 4.1.

The following values are derived for plies containing unidirectional fibers. From those, the properties of multiaxially aligned laminated plies may be derived, see 2.3 and 2.4. Chopped strand mats are considered separately in 2.2.3.
Table 4.1 Generic constituent material properties

<table>
<thead>
<tr>
<th></th>
<th>Fibers</th>
<th>Matrices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-Glass</td>
<td>Aramid</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.54</td>
<td>1.44</td>
</tr>
<tr>
<td>Parallel to fibers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>73000</td>
<td>124000</td>
</tr>
<tr>
<td>Perpendicular to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fibers</td>
<td>73000</td>
<td>6900</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>30000</td>
<td>28000</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>--</td>
<td>0.36</td>
</tr>
</tbody>
</table>

2.2.3 Stiffness properties of chopped strand mat

The Young’s modulus of a chopped strand mat (CSM) laminate can be calculated as:

\[
E_{CSM} = \frac{3}{8} E_{11} + \frac{5}{8} E_{22}
\]

\[
G_{CSM} = \frac{E_{CSM}}{2(1 + \nu_{CSM})}
\]

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

2.3 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. 2.3.1). In a second step, the stiffness matrix \( Q \) is transformed to the global coordinate system, resulting in the transformed stiffness matrix \( Q' \) (ref. 2.3.2). From this, the engineering constants of each ply in the global laminate coordinate system are determined in a third step (see 2.4).

2.3.1 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:

\[
Q_{11} = \frac{E_{11}}{1 - \nu_{12} \cdot \nu_{21}}
\]

\[
Q_{12} = \frac{\nu_{21} \cdot E_{11}}{1 - \nu_{12} \cdot \nu_{21}}
\]

\[
Q_{22} = \frac{E_{22}}{1 - \nu_{12} \cdot \nu_{21}}
\]

\[
Q_{33} = G_{12} \cdot a
\]

\( Q = \) Stiffness matrix of orthotropic layer in local ply coordinate system

\( a = \) 1,0 for a non-woven fabric

\( = 1,2 \) for satin (1×8 or 1×6) weave style fabrics

\( = 1,5 \) for twill (2×2, 3×1, 4×4) weave style fabrics

\( = 2,0 \) for plain (1×1) weave style fabrics
Stiffness matrix components \( Q \) for chopped strand mat (CSM) are to be derived using the above equations, too, where:
\[
E_{11} = E_{22} = E_{CSM} \\
\nu_{12} = \nu_{21} = 0.28 \\
G_{12} = G_{CSM}
\]

2.3.2 Angle transformation for single unidirectional ply stiffnesses to global coordinate system

The following formulae are used to transform elasto-mechanical properties found in 2.3.1 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 “\( \Theta \)”.

\[
Q_{11}' = Q_{11} \cdot \cos^4 \Theta + 2 \cdot (Q_{12} + 2 \cdot Q_{33}) \cdot \sin^2 \Theta \cdot \cos^2 \Theta + Q_{22} \cdot \sin^4 \Theta \\
Q_{22}' = Q_{11} \cdot \sin^4 \Theta + 2 \cdot (Q_{12} + 2 \cdot Q_{33}) \cdot \sin^2 \Theta \cdot \cos^2 \Theta + Q_{22} \cdot \cos^4 \Theta \\
Q_{23}' = Q_{22} \cdot (Q_{22} + Q_{12} - 2 \cdot Q_{33}) \cdot \cos \Theta \cdot \sin \Theta - (Q_{11} + Q_{12} + 2 \cdot Q_{33}) \cdot \sin \Theta \cdot \cos \Theta \\
Q_{13}' = Q_{12} \cdot Q_{11} + Q_{22} \cdot Q_{12} - 2 \cdot Q_{33} \cdot \sin^2 \Theta \cdot \cos^2 \Theta + Q_{12} \cdot (\sin^2 \Theta + \cos^2 \Theta) \\
Q_{33}' = (Q_{11} + Q_{22} - 2 \cdot Q_{12} - 2 \cdot Q_{33}) \cdot \cos^3 \Theta \cdot \sin \Theta - (Q_{11} - Q_{12} + 2 \cdot Q_{33}) \cdot \cos \Theta \cdot \sin^3 \Theta
\]

\( \Theta \) = Angle of transformation

\( Q' \) = Transformed stiffness matrix of orthotropic layer in global coordinate system

2.4 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 \( A_L \):

\[
A_{11L} = \sum_{i=1}^{n} Q_{11i} \\
A_{12L} = A_{21} = \sum_{i=1}^{n} Q_{12i} \\
A_{13L} = A_{31} = \sum_{i=1}^{n} Q_{13i} \\
A_{22L} = \sum_{i=1}^{n} Q_{22i} \\
A_{23L} = A_{33} = \sum_{i=1}^{n} Q_{23i} \\
A_{33L} = \sum_{i=1}^{n} Q_{33i}
\]

Bending extension matrix \( B_L \):

All forced to be zero:

\[
B_{11L} = B_{12L} = B_{13L} = B_{21L} = B_{22L} = B_{23L} = B_{31L} = B_{32L} = B_{33L} = 0
\]

Bending matrix \( D \):

\[
D_{11L} = \frac{1}{2} \sum_{i=1}^{n} Q_{11i} \left( z_i^3 - z_{i-1}^3 \right) \\
D_{12L} = \frac{1}{3} \sum_{i=1}^{n} Q_{12i} \left( z_i^3 - z_{i-1}^3 \right) \\
D_{13L} = \frac{1}{3} \sum_{i=1}^{n} Q_{13i} \left( z_i^3 - z_{i-1}^3 \right) \\
D_{22L} = \frac{1}{3} \sum_{i=1}^{n} Q_{22i} \left( z_i^3 - z_{i-1}^3 \right) \\
D_{23L} = \frac{1}{3} \sum_{i=1}^{n} Q_{23i} \left( z_i^3 - z_{i-1}^3 \right) \\
D_{33L} = \frac{1}{3} \sum_{i=1}^{n} Q_{33i} \left( z_i^3 - z_{i-1}^3 \right)
\]

\( z_i \) are distances from ply surfaces to the laminate midplane as depicted in Fig. 4.2
Fig. 4.2 Ply definitions

Resulting in the ABDL matrix:

$$
\begin{bmatrix}
A_{11L} & A_{12L} & A_{13L} & 0 & 0 & 0 \\
A_{21L} & A_{22L} & A_{23L} & 0 & 0 & 0 \\
A_{31L} & A_{32L} & A_{33L} & 0 & 0 & 0 \\
0 & 0 & 0 & D_{11L} & D_{12L} & D_{13L} \\
0 & 0 & 0 & D_{21L} & D_{22L} & D_{23L} \\
0 & 0 & 0 & D_{31L} & D_{32L} & D_{33L}
\end{bmatrix}
$$

And the inverse ABDL matrix:

$$
\begin{bmatrix}
a_{11L} & a_{12L} & a_{13L} & 0 & 0 & 0 \\
a_{21L} & a_{22L} & a_{23L} & 0 & 0 & 0 \\
a_{31L} & a_{32L} & a_{33L} & 0 & 0 & 0 \\
0 & 0 & 0 & d_{11L} & d_{12L} & d_{13L} \\
0 & 0 & 0 & d_{21L} & d_{22L} & d_{23L} \\
0 & 0 & 0 & d_{31L} & d_{32L} & d_{33L}
\end{bmatrix}
\begin{bmatrix}
a & b \\
b & d_{LL}
\end{bmatrix}^{-1}
\begin{bmatrix}
A & B \\
B & D_{LL}
\end{bmatrix}
$$

The engineering constants for the multiply layer are:

$$
E_x = \frac{1}{t \cdot a_{11L}},
\quad E_y = \frac{1}{t \cdot a_{22L}},
\quad G_{xy} = \frac{1}{t \cdot a_{33L}},
$$

$$
v_{xy} = -\frac{a_{12L}}{a_{11L}}
$$

The following layer stiffness values will be used for buckling analysis in 6.2:

$$
Q_{11}'_L = \frac{A_{11L}}{t_L},
Q_{12}'_L = Q_{21}'_L = \frac{A_{12L}}{t_L},
Q_{22}'_L = \frac{A_{22L}}{t_L},
Q_{33}'_L = \frac{A_{33L}}{t_L}
$$

\( t_L \) = thickness of single or multiply layer

2.5 Laminate stiffness

2.5.1 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 \( i \) of this compound. The following is also valid for determining the properties of sandwich skins each:

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

$$
E_{x, \text{laminate}} = \frac{\sum E_{x,i} \cdot t_i}{\sum t_i},
\quad E_{y, \text{laminate}} = \frac{\sum E_{y,i} \cdot t_i}{\sum t_i},
\quad G_{xy, \text{laminate}} = \frac{\sum G_{xy,i} \cdot t_i}{\sum t_i},
$$

$$
t_{\text{laminate}} = \sum t_i
$$

\( E_{x,i}, G_{xy,i} \) = engineering constants of layer

\( t_i \) = thickness of layer \( i \)

These mean values should only be used for in-plane assessments or for very homogenous 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 centroid 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 \( G_{A_u} \) of a single skin laminate per unit width:

$$
G_{A_u} = \sum G_i \cdot t_i
$$
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

### 2.5.2 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 simple 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.

### 2.6 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.

#### 2.6.1 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 approximately 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 Fig 4.3, 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

\( w = \) width of plating supported, measured from centre to centre of the adjacent unsupported fields

![Fig. 4.3 Effective width of plating](image-url)

Additionally the beams foot width “\( w_f \)” can be added to \( w_{eff} \), see Fig. 4.4.

![Fig. 4.4 Typical top hat stiffener](image-url)

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

#### 2.6.2 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

#### 2.6.3 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. Laterally loaded plates

#### 3.1 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.

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 of plates. 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 contributions due to membrane effects, like calculated using other methods or FEA, will generally not be accepted.

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 focusing 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 are to be used.

3.2 Parameters

Laminated plates are to be characterized by the following parameters:

3.2.1 Structural parameters

\[ E_{I_x} = \text{panel bending stiffness in panels global } x\text{-direction} (\text{about panels global } y\text{-direction}) \]

\[ E_{I_y} = \text{panel bending stiffness in panels global } y\text{-direction} (\text{about panels global } x\text{-direction}) \]

\[ t_c = \text{thickness of sandwich core} \]

\[ z_i = \text{distance from a certain location on the neutral axis in bending} \]

These values are calculated in 2.2 or 2.3.

3.2.2 Geometrical parameters

\[ s_x = \text{unsupported span in global } x\text{-direction} \]

\[ s_y = \text{unsupported span in global } y\text{-direction} \]

Boundary conditions: all edges fixed or all edges simply supported.

3.2.3 Load details and design pressures

Lateral design pressures according to Section 3, B. are to be applied.

3.2.4 Geometric aspect ratio \( a_r \)

\[ a_r = \frac{s_x}{s_y} \]

3.2.5 Effective aspect ratio

For orthotropic panel properties with \( E_{I_x} \) not equal \( E_{I_y} \), the geometrical aspect ratio \( a_r \) needs to be corrected:

\[ a_{r,\text{corr}} = a_r \cdot \sqrt{\frac{E_{I_y}}{E_{I_x}}} \]

For the purpose of further calculations, the corrected aspect ratio \( a_{r,\text{corr}} \) has to be related to the span of the panel that is considered to be effective to take up the major bending and shear loads (see 3.1) and will be called “effective span \( s_{\text{eff}} \)”:

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

If \( a_{r,\text{corr}} \) is < 1, then \( a_{r,\text{eff}} = \frac{1}{a_{r,\text{corr}}} \)

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

3.2.6 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 neighboring panel sizes.

In specific cases, hull chines 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 \( \omega \) shall be close to 90° to allow for such assumption, see Fig 4.5. 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 has to be multiplied by the correction factor \( c_c \):

\[ s_{x/y} = \text{corrected panel span} \]

\[ = c_c \cdot s_c \]

\[ c_c = \text{correction factor} \]

\[ s_c = \text{panel span} \]
c) The suitability of this approach might not cover all occurring variants of design and in doubt will need to be confirmed by GL.

d) A panel divided according to the approach offered here, will possibly require a re-orientation of the effective span. The boundary condition used for following scantling calculations may be assumed as “fixed” along the new boundary.

e) Pressures applicable for the so determined panels will be derived by calculating average values, including considering the fraction of their individual perimeter span.

This approach is inventing a virtual chine at a point or line having a deadrise of 40° to the horizontal. However, transverse panel spans are measured from a point or line having

- 15° less deadrise (absolute 25° deadrise) for the upper panel
- 15° more deadrise (absolute 55° deadrise) for the lower panel

With no longitudinal girders arranged along the full hull section perimeter (Fig. 4.7), this division produces 2 virtual chines (Ps and Stb) and thus 3 panels, one of them across centreline. With the existence of a centreline –or two slightly off centreline girders (Fig. 4.8), the method provides 2 panels each Ps. and Stb. between the girder and the gunwhale.

Guidance note: Virtual chines

Inventing a „virtual chine“ in first principles of panel structural design gives rise to the fact that a “turn-of-the-bilge”-effect is providing virtual support for a panel spanning across a very great width. This support is valid/applicable under the following aspects:

a) Approach is applicable for the case the panel does not exhibit a natural stiffener, like a geometric hard chine or a distinct area of pronounced great curvature, but a great change in deadrise tangent angle, comparing both transverse boundaries.

b) Dividing a panel like proposed is in general only valid when the panel athwartships spans over at least 45 % of the perimeter of the hulls section (from gunwale to gunwale), i.e. will only be appropriate for a section with either no longitudinal girders, one centreline girder or two only slightly off-centreline girders.

Fig. 4.5 Corrected span

Fig. 4.6 Panel span correction factor $c_s$ 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 centerline without the existence of a centerline girder, e.g. where the panels are delimited by off-centre longitudinals. For determination of $c_s$ see Fig 4.6.

transverse panel span of panel above virtual chine

transverse panel span of panel below virtual chine

55° tangent to horizontal

25° tangent to horizontal

Fig. 4.7 Panel span with no longitudinal girders

transverse panel span of panel above virtual chine

transverse panel span of panel below virtual chine

55° tangent to horizontal

25° tangent to horizontal

Fig. 4.8 Panel span with existence of longitudinal girder
3.2.7 Plate curvature

Curvature will only be considered if the plate is curved in the direction of the effective span $s_{\text{eff}}$, see Fig. 4.9.

Plate curvature correction coefficient:

$$r_c = 1,15 - \left( 5 \cdot \frac{h}{s_{\text{eff}}} \right)$$

where:

$$0,03 < \frac{h}{s_{\text{eff}}} < 0,1$$

and:

$$r_{c,\text{min}} = 0,65$$

![Fig. 4.9 Plate curvature](image)

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

As mentioned in 3.1, the calculation is being reduced to the assessment of a panel strip of one unit width (e.g. 1 mm).

### 3.3.1 Maximum bending moment

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

- $\beta$ = see Table 4.2
- $p_d$ = lateral design pressure on associated plating according to Section 3, B.
- $s_{\text{eff}}$ = effective panel span
- $r_c$ = curvature correction coefficient

#### 3.3.2 Maximum reaction shear force

The maximum shear force reaction, occurring as a line force, emerges at the centre of the panel edges which are adjacent to the effective panel span, see Fig. 4.10:

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

- $\gamma$ = see Table 4.2
- $p_d$ = lateral design pressure on associated plating according to Section 3, B.
- $s_{\text{eff}}$ = effective panel span

Should a sandwich panel be constructed using a core with different shear strength properties in different directions (Honeycomb), the “secondary” maximum shear reaction line force has to be determined. This force occurs at the panel edges spanning alongside the effective span, see Fig. 4.10:

$$F_{q,\text{sec}} = \gamma_t \cdot p_d \cdot s_{\text{eff}}$$

- $\gamma_t$ = see Table 4.2

Curvature of a panel is considered having no effect on the magnitude of shear reaction forces.

### Table 4.2 Values $\beta$, $\alpha$, $\gamma$

<table>
<thead>
<tr>
<th>$ar_{\text{eff}}$</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
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<td>0.3762</td>
<td>0.4530</td>
<td>0.5172</td>
<td>0.5688</td>
<td>0.6102</td>
<td>0.6713</td>
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<td>0.0770</td>
<td>0.0906</td>
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<td>0.1110</td>
<td>0.1335</td>
<td>0.1400</td>
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<td>0.1421</td>
</tr>
<tr>
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<td>0.4780</td>
<td>0.4910</td>
<td>0.4990</td>
<td>0.5030</td>
<td>0.5050</td>
<td>0.5020</td>
<td>0.5010</td>
<td>0.5000</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>0.4200</td>
<td>0.3850</td>
<td>0.3620</td>
<td>0.3490</td>
<td>0.3410</td>
<td>0.3370</td>
<td>0.3350</td>
<td>0.3380</td>
<td>0.3390</td>
<td>0.3400</td>
</tr>
</tbody>
</table>

<table>
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<th>$ar$</th>
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<th>1.2</th>
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<th>1.6</th>
<th>1.8</th>
<th>2</th>
<th>$\infty$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.3834</td>
<td>0.4356</td>
<td>0.4680</td>
<td>0.4872</td>
<td>0.4974</td>
<td>0.5000</td>
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<tr>
<td>$\alpha$</td>
<td>0.0138</td>
<td>0.0188</td>
<td>0.0226</td>
<td>0.0251</td>
<td>0.0267</td>
<td>0.0277</td>
<td>0.0284</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.4200</td>
<td>0.4550</td>
<td>0.4780</td>
<td>0.4910</td>
<td>0.4990</td>
<td>0.5030</td>
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<tr>
<td>$\gamma_t$</td>
<td>0.4200</td>
<td>0.3850</td>
<td>0.3620</td>
<td>0.3490</td>
<td>0.3410</td>
<td>0.3370</td>
<td>0.3400</td>
</tr>
</tbody>
</table>
3.3.3 Maximum lateral deflection

\[ z_{\text{max}} = \frac{\alpha \cdot p_d \cdot s_{\text{eff}}}{12 \cdot E I_{\text{eff}}} \]

\[ \alpha = \text{see Table 4.2} \]

\[ p_d = \text{lateral design pressure on associated plating according to Section 3, B.} \]

\[ s_{\text{eff}} = \text{effective panel span} \]

\[ E I_{\text{eff}} = \text{plate bending stiffness relevant for the direction of the effective panel span} \]

3.4 Determination of laminate strains and stresses

3.4.1 Laminate strains

The structural performance of a laterally loaded plate is characterized 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:

\[ \varepsilon_i = \frac{M_{b\text{-max}} \cdot z_i}{E I_{\text{eff}}} \]

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 strains defined in 8. Apart from the pure bending strains, stability issues such as skin wrinkling need to be considered, relate to 6.

3.4.2 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 has to transmit the through-thickness shear forces. A certain contribution by the skins is assumed.

Core shear stress is calculated as being:

\[ \tau_c = \frac{F_q}{t_c + \frac{t_{s1} + t_{s2}}{2}} \]

\[ F_q = \text{see 3.3.2} \]

\[ = F_{q\text{-max}} \text{ for core evaluation along effective panel span} \]

\[ = F_{q\text{-sec}} \text{ for core evaluation across effective panel span} \]

\[ t_c = \text{core thickness} \]

\[ t_{s1}, t_{s2} = \text{thickness of skins} \]

The calculated stress may not exceed the allowable strains defined in 8.

4. Laterally loaded beams

4.1 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 Fig. 4.11.

Typically, the beams consist of a web(s) designed to carry the shear force and flanges to carry the bending load. The web may be attached vertically or inclined to the shell (only the structural height times the thickness as effective shear area is to be considered). One flange is usually comprised by a certain amount of attached plating (see effective width) and possible additional pads beneath the web. The other flange is comprised by the “capping” of the beam.

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

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”.

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.

Laminated beams including their associated plating are to be characterized by the following parameters.

### 4.2 Parameters

#### 4.2.1 Structural parameters

The following parameters have been determined in 2.6:

\[
EI = \text{beam bending stiffness including associated plating}
\]

\[
GA = \text{shear stiffness of webs}
\]

\[
z_i = \text{distance from a certain location within the beam to the neutral axis in bending}
\]

\[
w_{\text{eff}} = \text{effective width of plating}
\]

#### 4.2.2 Geometrical parameters

\[
\ell = \text{unsupported length of the beam}
\]

\[
w = \text{load width}
\]

Boundary condition (all edges fixed or all edges simply supported).

#### 4.2.3 Load details

For panel design pressures see Section 3.

#### 4.2.4 Beam curvature correction

Curvature correction coefficient:

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

Where:

for: \( 0.03 < \frac{h}{\ell} < 0.1 \)

and:

\[
r_{cb,\text{min}} = 0.65
\]

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

#### 4.3.1 Maximum bending moment

\[
M_{b,\text{max}} = \frac{P_d \cdot w \cdot \ell^2 \cdot c_b}{c_b}
\]

\( P_d \) = lateral design pressure on associated plating according to Section 3, B.

\( w \) = load width

\( \ell \) = length of beam between supports

\( c_b \) = boundary condition coefficient

= 12 for fixed end supports

= 8 for simply supported

#### 4.3.2 Maximum reaction shear force

The maximum shear force typically occurs at the boundaries. For symmetrical boundary conditions the maximum shear force is:

\[
F_{q,\text{max}} = \frac{P_d \cdot \ell \cdot w}{2}
\]

\( P_d \) = see Section 3, B.

\( \ell \) = see 4.3.1

\( w \) = see 4.3.1

Reaction shear forces for unsymmetrical boundaries have to be determined individually.

#### 4.3.3 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:

\[
z_{\text{max}} = \frac{P_d \cdot w \cdot \ell^4 \cdot c_d}{384 \cdot EI}
\]

\( c_d \) = boundary condition coefficient

= 12 for fixed end supports

= 8 for simply supported
4.4 Beam construction notes

4.4.1 In general, the bonding laminate (if not integral with the shear web) of a shear web needs to have the same shear stiffness/strength as the web. The lap of the bonding has to be large enough to transmit in-plane shear forces. It is important to place the bonding tapes using the specified fiber orientations throughout, see Fig. 4.12.

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.

4.4.2 The requirement for a sufficient amount of shear buckling stiffness of web laminates may lead to the inclusion of stabilizing 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 to prevent shear buckling.

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

4.4.4 Web laminates necessary to carry the shear loads should in general continue across the capping laminate and be interspersed with the capping laminate.
Critical wrinkling strain for sandwich cored with honeycomb:

\[ \varepsilon_{sw\text{-crit}} = 0.5 \left( \frac{E_{bf} \cdot E_c \cdot G_c}{E_f} \right)^{1/3} \]

Critical buckling strain

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

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

- \( E_{\text{a-mean}} \) = mean Young’s modulus in load direction (a) of full laminate (incl. core)
- \( t_{\text{tot}} \) = 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
- \( h(\alpha) + q \cdot \beta \)
- \( q \) = boundary condition adjustment factor
- \( 2 \) for unloaded edges simply supported
- \( 2,36 \) for unloaded edges clamped
- \( h(\alpha) \) = see Fig. 4.13
- \( \alpha \) = modified aspect ratio
- \( \beta \) = “Seydel” orthotropic parameter
- \( D11 = \frac{a}{b} \sqrt{\frac{D22}{D11}} \)
- \( D12 + 2 \cdot D33 \sqrt{D11 \cdot D22} \)

Coefficients from the laminate’s bending matrix D:

\[ D11 = \sum_{i=1}^{n} Q11'_{Li} \cdot \frac{1}{3} \left( z_i^3 - z_{i-1}^3 \right) \]
\[ D12 = \sum_{i=1}^{n} Q12'_{Li} \cdot \frac{1}{3} \left( z_i^3 - z_{i-1}^3 \right) \]
\[ D22 = \sum_{i=1}^{n} Q22'_{Li} \cdot \frac{1}{3} \left( z_i^3 - z_{i-1}^3 \right) \]
\[ D33 = \sum_{i=1}^{n} Q33'_{Li} \cdot \frac{1}{3} \left( z_i^3 - z_{i-1}^3 \right) \]

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 2.4.

\( z_i \) are distances from ply surfaces to the laminate midplane as depicted in Fig. 4.2.
6.3 Buckling of orthotropic plates under in-plane shear loads

The general provisions 6.2.1 apply.

6.3.1 Critical buckling strain

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

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

If \( \alpha \leq 1 \), then:

- \( w = b \)
- \( D_a = D_{11} \)
- \( D_b = D_{22} \)

If \( \alpha > 1 \), then:

- \( \alpha = \frac{\alpha}{1} \)
- \( w = a \)
- \( D_a = D_{22} \)
- \( D_b = D_{11} \)

\( b \) = plate width in X,1 direction acc. to Fig. 4.14
\( a \) = plate width in Y,2 direction acc. to Fig. 4.14

7. Further considerations

7.1 Through-thickness effects

In general it is preferred to have a fiber-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.

7.2 Minimum shell thickness

Apart from the provisions explicitly defined in this Section, no particular algorithm has been implemented to define a minimum shell or skin thickness for hull laminates, covering wear and tear and local forces or impact, e.g. when docking, dry docking or from collision with floating or submerged debris. Guidance can be given upon request.
8. Allowable strains, safety factors and maximum deflections

For fiber 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 fiber reinforced composites under the condition that the composite shows a fiber-dominant load transfer. These limits provide a sufficient margin over interlaminar micro cracking and fiber failure in all inplane directions.

For adhesive bonds, the structural evaluation of sandwich cores and the evaluation of stability criteria, safety factors are serving to achieve sufficient integrity.

Further to that, a deflection criterion has to be fulfilled.

8.1 Allowable laminate strains

8.1 Maximum strain for laminates in axial tension/compression is to be:

- 0.25% (for standard modulus, intermediate modulus or high strength carbon fiber laminates, built as wet, vacuum or in infusion technology)
- 0.275% (for standard modulus, intermediate modulus or high strength carbon fiber laminates, built using pre-preg technology)
- Smaller value of one of the above and UCS/3 (for laminates consisting of high modulus carbon fibers, (“UCS”=ultimate compressive strain)
- 0.35% (for E-Glass laminates)

GL reserves the right to inquire test certificates for tests on ultimate compressive strain, using ASTM D-694. Tests need to be carried out at accredited, independent laboratories.

Maximum allowable in-plane shear strain is to be:

- 0.45% (for standard modulus, intermediate modulus or high strength carbon fibers laminates, built as wet, vacuum or in infusion technology)
- 0.49% (for standard modulus, intermediate modulus or high strength carbon fibers laminates, built using pre-preg technology)
- Smaller value of one of the above and UCS · 0.6 (for laminates consisting of high modulus carbon fibers)
- 0.7% (for E-Glass laminates)

8.2 Sandwich core safety factors

The following methodology applies for laterally loaded sandwich structures. The safety factors applied for different locations of the yacht’s hull are attributed by whether the occurring sea loads are of mainly hydro-dynamic or hydro-impact character (see Table 4.3). This includes characteristics such as shear strength offset due to high strain rate loadings, energy take-up and linearity/non-linearity of stress/strain behavior, where in all cases the basic static shear strength (msnv: manufacturer’s specified minimum value) serves as a reference for application of safety factors.

8.3 Safety factors and allowable deflections

- Factor of 2.5 vs. panel buckling and 2.0 vs. skin wrinkling on the strains determined according to 6.
- Factor of 2.5 vs. ultimate shear strength in adhesive bond using well-proven structural adhesives.
- Maximum allowable 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
- Appropriate safety of skin/core bond.

9. Construction and design details

9.1 Consequences of elasticity

Unlike metals, fiber reinforced composites used for marine applications exhibit almost linear elastic behaviour to failure. This is as long as the structural response is fiber-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 as critical. This is valid for in-plane loads with fiber dominated load absorption. However, through-thickness loading (especially shear and tension) can not 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.
### Table 4.3: Sandwich core safety factors

<table>
<thead>
<tr>
<th>Core type</th>
<th>Ultimate shear elongation</th>
<th>Safety factors applicable for hull shell and watertight bulkheads</th>
<th>Safety factors for deck shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balsa / Aramid honeycomb</td>
<td>&lt; 10 %</td>
<td>2,5</td>
<td>2,5</td>
</tr>
<tr>
<td>Medium elongation, e.g. cross-linked PVC</td>
<td>&lt; 35 %</td>
<td>2,2</td>
<td>2,5</td>
</tr>
<tr>
<td>High elongation, e.g. linear PVC and SAN*</td>
<td>&gt; 35 %</td>
<td>1,7</td>
<td>2,5</td>
</tr>
</tbody>
</table>

* = carrying a type approval certificate from an IACS classification society confirming suitability for being used in slamming areas or has passed an approved test using similar criteria.

### 9.2 Recommendations

The following recommendations do not claim to be all-inclusive:

- In general, the basic laminate stacking sequence shall be homogenous; preferably symmetrical and balanced, if not particular attention has to 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). Exceptions are the following components/items:
  - Mainly in-plane shear loaded webs or girders, stiffeners, frames
  - Local tape reinforcements
  - Grouping of plies with the same fiber 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 take 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.

### 9.3 Details

Structural details are subject to examination by GL. In general the following provisions shall be observed:

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

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

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

- Exposed fibers and sandwich cores shall be sealed or clashed with laminate.

- Through-sandwich penetrations have to be adequately designed, e.g. installing appropriate skin ties and/or back-fill with structural filler.
Section 5

Design and Scantlings for Steel and Aluminium Structures

A. General

1. Scope

The following design principles and scantling requirements apply to the structure of sailing yachts with $24 \leq L \leq 48$ m of normal monohull form made from steel or aluminium alloys.

The following contains definitions and principles for using the scantling formulae as well as indications concerning structural details.

2. Materials

The requirements for construction materials are defined in Section 2, B. and C. Materials with properties deviating from the requirements therein may only be used upon special GL acceptance.

3. Welding

Welding work is to be in compliance with the GL Rules for Welding (II-3). An excerpt thereof is given in Section 2, D.

B. Principles for Structural Design

1. General structural arrangement

1.1 The hull structural arrangement shall consist of an effective strengthening system of bulkheads, web frames, longitudinal girders, etc. as well as transverse frames and/or longitudinal stiffeners. Longitudinal stiffeners are to be supported by transverse web frames or transverse bulkheads. Transverse frames are to be supported by longitudinal girders or other longitudinal structural members, see Fig. 5.1 and Fig. 5.2.

1.2 Care is to be taken to ensure structural continuity and to avoid sharp corners. Therefore abrupt discontinuities of longitudinal members are to be avoided and where members having different scantlings are connected with each other, smooth transitions have to be provided. At the end of longitudinal bulkheads or continuous longitudinal walls, suitable scarping brackets are to be provided.

1.3 Bottom longitudinals are preferably continuous through the transverse elements. Where longitudinals are interrupted in way of watertight bulkheads or reinforced transverse structures, the continuity of the structure is to be maintained by means of brackets penetrating the transverse element. GL may allow double brackets welded to the transverse element, provided that special attention is given to the alignment of longitudinals and full penetration welding is used.

1.4 Floors are to be fitted in line with transverse frames or transverse webs. Alternatively, floors may terminate at longitudinal girders which in turn are supported by transverse bulkheads or deep web rings.

1.5 Where frames, beams and stiffeners are intercostal at an intersecting member, the connections have to provide continuity of strength.

1.6 Sailing yachts shall have transverse bulkheads or equivalent structures in way of mast(s) in order to achieve adequate transverse rigidity. Bulkheads or deep brackets are to be provided in way of chain plates. Any other arrangement shall be subject to special approval.

2. Longitudinal strength

A longitudinal strength calculation is to be carried out using the loads defined in Section 3, E.

3. Bulkheads

3.1 Number and location of watertight bulkheads should be considered in an early design phase to ensure compliance with other relevant regulations, if applicable. For the arrangement of bulkheads see also GL Rules for Yachts ≥ 24 m (I-3-2), Section 3, D.8.

3.2 Collision bulkhead

The collision bulkhead shall extend watertight up to the weather deck. Steps or recesses may be permitted. Openings in the collision bulkhead shall be watertight and permanently closed in sailing condition. Closing appliances and their number shall be reduced to the minimum, compatible with the design and proper working of the yacht.

Where pipes are piercing the collision bulkhead, screw down valves are to be fitted directly at the collision bulkhead. Such valves are to be operable from outside the forepeak.
3.4 Openings in watertight bulkheads

In watertight bulkheads other than collision bulkheads, watertight doors may be fitted. Below the deepest load waterline, they are to be constructed as slid-

3.4.1 Watertight bulkhead doors and their frames are to be tested before they are fitted onboard by a head of water corresponding to the freeboard deck height or the results from damage stability calculation. Alternatively watertight doors may be used which have been type approved in accordance with GL special acceptance procedure. After having been fitted on board, the doors are to be soap-tested for tightness and to be subject to an operational test.

3.4.2 Penetrations through watertight bulkheads

Where bulkhead fittings are penetrating watertight bulkheads, care is to be taken to maintain water tightness. For penetrations through the collision bulkhead 3.2 is to be observed.

4. Openings

4.1 In highly stressed areas openings are to be generally avoided.

4.2 Corners of all openings in strength structures are to be well rounded. If necessary, the shape of the openings is to be designed to reduce stress concentrations.

5. Bottom structure

5.1 Generally, a centerline girder shall be fitted for docking purposes unless sufficient strength and stiffness is already achieved by the external keel or the bottom shape. Additional bottom girders may be appropriate. The centerline and the off-centerline bottom girders are to extend as far forward and aft as practicable. The girders shall be fitted with a continuous face plate. Lightening holes in girders shall generally not exceed half the depth of the girder and their length shall not exceed half the frame spacing.

5.2 Floors or equivalent structural components are to be fitted in the area of the engine foundations, the rudder skeg and the propeller bracket, if applicable. Plating is to be locally increased in way of rudder bearings, propeller brackets by 1.5 times of the adjacent plate thickness.

5.3 Manholes and other openings are not to be located at the ends of floor or girder spans, unless shear stress checks are carried out in such areas.
5.4 The bottom structure in way of the ballast keel is to be reinforced due to additional loads transmitted by the keel. Special care is to be taken with the structural support of fin keel’s leading and trailing edge.

6. Engine foundation
The foundation shall be constructed for the proper transmission of forces in the transverse and longitudinal directions. Longitudinal girders forming seatings of the engine, the gearbox and the thrust block shall therefore extend to the engine room bulkheads and are to be supported transversely by floors, web frames or wing bulkheads.

7. Side structure and bulwarks
7.1 Side frames shall be connected to keel floors and deck beams by brackets. Alternatively, a continuous transition between such elements is to be adequately rounded. Continuity of longitudinal stiffeners is to be ensured, if applicable.

7.2 Bulwark plating is to be determined by applying the side design pressure for the relevant vertical height. Bulwark stanchions must be in line with transverse beams or adequate substructure must be provided by other means. Bulwarks are to be provided with freeing ports of sufficient size, see GL Rules for Yachts ≥ 24 m (I-3-2), Section 3, D.5.

8. Tank structures
8.1 Tanks longer or wider than 0,1 L require effective internal baffles. It is recommended that the degree of perforation is no less than 5 % and no more than 10 %, but under no circumstances more than 50 % of the unperforated section area of the tank baffle.

8.2 Fresh water tanks are to be separated from other tanks such as waste water tanks by cofferdams. The same applies to fuel tanks. Generally, also tanks such as lubricating or hydraulic oil tanks shall be separated from each other by equivalent means.

9. Deck
9.1 In case of longitudinal deck stiffeners, deck beams are to be located in way of the vertical web frames of the side shell. Structural continuity of the stiffeners is to be ensured, see Fig. 5.1.

9.2 In case of a transversely stiffened deck, deck beams are to be generally fitted at every frame and shall be in line with the side stiffening members, see Fig. 5.2.

10. Superstructures and deckhouses
10.1 Ends of superstructures and deckhouses are to be sufficiently supported by bulkheads, pillars or other equivalent arrangements. Superstructure front and aft bulkheads are to be aligned with bulkheads in the hull or must be equivalently supported by pillars. In extension of superstructures and deckhouses, girders shall be arranged under the main deck extending at least three frame spaces beyond the ends of the longitudinal walls. These girders shall overlap the longitudinal walls at least by two frame spaces.

10.2 Web frames or partial bulkheads are to be provided to ensure transverse rigidity in large deckhouses. The strength members are to be suitably reinforced in the area of masts and other load concentrations. As a rule, the spacing of stiffeners on sides of superstructures and deckhouses are to be the same as those of beams on supporting decks.

10.3 Structural discontinuities and rigid points are to be avoided. When the strength of a structural element is reduced by the presence of an attachment or an opening, proper compensation is to be provided.

11. Pillars
For the structural arrangement of pillars see C.5.

12. Design assumptions
12.1 Required sectional properties
The required section moduli and web areas are related, on principle, to an axis which is parallel to the connected plating. For profiles usual in the trade and connected vertically to the plating, in general the appertaining sectional properties are given in tables. Where webs of stiffeners and girders are not fitted vertically to the plating (e.g. frames on the shell in the flaring fore body) the sectional properties (moment of inertia, section modulus and shear area) have to be determined for an axis which is parallel to the plating. For bulb profiles and flat bars the section modulus of the inclined profile can be calculated approximately by multiplying the corresponding value for the vertically arranged profile by \( \sin \alpha \), where \( \alpha \) is the smaller angle between web and attached plating.

12.2 Curved plate panels
The thickness of curved plate panels may be reduced by applying the following correction factor \( f_c \) in the formula of C.2.3.

\[
f_c = 1,1 - 3 \cdot \frac{h}{s} \quad \text{for} \quad \frac{1}{30} \leq \frac{h}{s} \leq 0,1
\]

\( h \) = according to Fig. 5.3

\( s \) = according to Fig. 5.3
12.3 Curved frames and girders

For curved frames and girders, the section modulus may be reduced by applying the factor $f_{cs}$ in the formula of C.3.2.

$$f_{cs} = 1,15 - 5 \frac{h}{s} \text{ for } 0,03 \leq \frac{h}{s} \leq 0,1$$

$h$ = according to Fig. 5.3

$s$ = according to Fig. 5.3

12.4 Unsupported span of stiffeners, frames

The unsupported span $\ell$ is the length of the stiffeners between two supporting girders or else their length including end attachments (brackets), see Fig. 5.4.

12.5 Unsupported span of transverses and girders

The unsupported span $\ell$ of transverses and girders is to be determined according to Fig. 5.5, depending on the type of end attachment. In special cases, the rigidity of the adjoining girders is to be taken into account when determining the span of girder.

$$c = \frac{a + b}{4}$$

12.6 End attachments

12.6.1 Definitions

For determining scantlings of beams, stiffeners and girders the terms "constraint" and "simple support" will be used.

"Constraint" will be assumed where for instance the stiffeners are rigidly connected to other members by means of brackets or are running throughout over supporting girders. "Simple support" will be assumed where for instance the stiffener ends are sniped or the stiffeners are connected to plating only, see also 12.8.

12.6.2 Design of details

Structural details are to be designed and constructed to minimize hard spots, notches and other structural discontinuities leading to stress concentrations. Therefore sharp corners and abrupt changes in sections are to be avoided. Toes of brackets and ends of members are not to terminate on plating without attachment to an adjacent member, unless specially approved.

12.7 Brackets

12.7.1 For the scantlings of brackets the required section modulus of the section is decisive. Where sections of different section moduli are connected to each other, the scantlings of the brackets are generally governed by the smaller section.

12.7.2 The thickness of the brackets is not to be less than:

$$t = c \cdot \sqrt{\frac{W}{k_l}} + t_k \quad [\text{mm}]$$

$c$ = 1,20 for non flanged brackets

$= 0,95$ for flanged brackets
k1 = material factor k for the section according to Section 2.B. and C.

W = section modulus of smaller section [cm³]

tmin = 5.5 mm

tmax = web thickness of smaller section

tk = corrosion allowance according to C.1.2

12.7.3 The arm length of brackets is not to be less than:

$$\ell = 46.2 \cdot \frac{W}{k_1} \cdot \sqrt{k_2 \cdot c_1}$$

$$\ell_{\text{min}} = 100 \text{ mm}$$

W = see 12.7.2

k1 = see 12.7.2

k2 = material factor k for the bracket, according to Section 2, B. or C.

$$c_1 = \sqrt{\frac{t}{t_a}}$$

ta = “as built” thickness of bracket [mm] ≥ t according to 12.7.2

The arm length ℓ is the length of the welded connection.

Note

For deviating arm lengths the thickness of brackets is to be estimated by direct calculations considering sufficient safety against buckling.

12.7.4 Where flanged brackets are used, the width of flange is to be determined according to the following formula:

$$b = 40 + \frac{W}{30} \text{ [mm]}$$

12.8 Snipped ends of stiffeners

Stiffeners may be snipped at the ends, if the thickness of the plating supported by stiffeners is not less than:

$$t = c \cdot \sqrt{\frac{p \cdot a \cdot (\ell - 0.5 \cdot a)}{R_{\text{eh}}}} \text{ [mm]}$$

p = design load in [kN/m²]

ℓ = unsupported length of stiffener [m]
a = spacing of stiffener in [m]

R_{\text{eh}} = minimum nominal upper yield point of the plating’s material [N/mm²] according to Section 2, B.

c = 15.8 for watertight bulkheads and for tank bulkheads

19.6 otherwise

12.9 Effective width of plating

12.9.1 Beams (stiffeners, frames, girders)

The effective width of plating \(e_m\) of frames and girders may be determined according to Table 5.1, considering the type of loading. Special calculations may be required for determining the effective width of one-sided or non-symmetrical flanges.

12.9.2 The effective cross sectional area of plates is not to be less than the cross sectional area of the beam flange.

12.9.3 The effective width of stiffeners and girders subjected to compressive stresses may be determined by proof of buckling strength, but is in no case to be taken greater than determined by 12.9.1.

### Table 5.1 Effective width of plating \(e_m\) of frames and girders

<table>
<thead>
<tr>
<th>ℓ / e</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>≥ 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e_{m1}/e)</td>
<td>0</td>
<td>0.36</td>
<td>0.64</td>
<td>0.82</td>
<td>0.91</td>
<td>0.96</td>
<td>0.98</td>
<td>1.00</td>
<td>1.0</td>
</tr>
<tr>
<td>(e_{m2}/e)</td>
<td>0</td>
<td>0.2</td>
<td>0.37</td>
<td>0.52</td>
<td>0.65</td>
<td>0.75</td>
<td>0.84</td>
<td>0.89</td>
<td>0.9</td>
</tr>
</tbody>
</table>

\(e_{m1}\) = is to be applied where girders are loaded by uniformly distributed loads or else by not less than 6 equally spaced single loads.

\(e_{m2}\) = is to be applied where girders are loaded by 3 or less single loads.

Intermediate values may be obtained by direct interpolation.

\(\ell\) = length between zero-points of bending moment curve, i.e. unsupported span in case of simply supported girders and 0.6 × unsupported span in case of constraint of both ends of girder

\(e\) = width of plating supported, measured from centre to centre of the adjacent unsupported fields
C. Scantlings

1. General

1.1 Rounding-off tolerances

If the determined plate thickness differs from full or half mm they may be rounded off to full or half mm up to 0,2 mm or 0,7 mm; above 0,2 and 0,7 mm they are to be rounded up.

1.2 Corrosion allowances

The following, reduced corrosion allowances may be applied for yachts, if special care for maintenance and special attention for measures of corrosion protection can be assumed.

1.2.1 Steel

The scantlings require the following allowances $t_k$ to the theoretical, rounded-off plate thickness:

- $t_k = 0,5 \text{ mm}$ in general
- $t_k = 0,7 \text{ mm}$ for lubrication in oil, gas oil or equivalent tanks
- $t_k = 1,0 \text{ mm}$ for water ballast and heavy oil tanks

for special applications $t_k$ shall be agreed with GL.

For all elements of the yacht's structure which are forming a boundary of tanks, the $t_k$ values for tanks have to be considered.

1.2.2 Aluminium alloys

Scantlings stipulated in these guidelines assume that the materials used are chosen and protected in such way that the strength lost by corrosion is negligible. If the measures for corrosion protection described in Section 2, E. are fully applied, the corrosion allowance $t_k$ can be assumed as 0 for the types of aluminium alloys defined in Section 2, C.3. and C.4.

1.3 Minimum plate thickness

In general the minimum plate thicknesses for steel and aluminium alloy structures defined in Table 5.2 shall be met. In exceptional cases other values may be agreed with GL.

<table>
<thead>
<tr>
<th>Element</th>
<th>Minimum thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom shell plating</td>
<td>0,9 $\sqrt{k \cdot L}$</td>
</tr>
<tr>
<td>Side shell plating</td>
<td>0,8 $\sqrt{k \cdot L}$</td>
</tr>
<tr>
<td>Deck plating</td>
<td>0,7 $\sqrt{k \cdot L}$</td>
</tr>
<tr>
<td>All other strength relevant plating</td>
<td>3,0</td>
</tr>
</tbody>
</table>

$k =$ material factor
$= $ for steel according to Section 2, B.1.1. and 1.2
$= $ for aluminium $= k_{Al}$ according to Section 2, C.6.

2. Plating

2.1 Keel

2.1.1 Flat plate keel and garboard strake

The width of the flat plate keel $b$ is not to be less than:

$$b = (650 + 5 \cdot \sqrt{k}) \text{ mm}$$

$k =$ material factor, see 2.3.1

2.1.2 The thickness of the flat plate keel is not to be less than:

$$t_{K\text{eel}} = t + 2,0 \text{ mm}$$

$t =$ thickness of the adjacent bottom plating [mm]

Where a single bottom plating is provided, the thickness of the flat plate keel and the garboard strake is to be adequately increased in the machinery space.

2.2 Bar keel

Where a bar keel is provided, its height $h$ and thickness $t$ are recommended to be determined according to following formulae:

$$h = (1,1 \cdot \sqrt{k}) \text{ mm}$$

$$t = (0,6 \cdot \sqrt{k}) \text{ mm}$$

$k =$ material factor, see 2.3.1

2.3 Hull shell, bulkheads and tanks

2.3.1 The thickness of the plating of hull, decks, superstructures, bulkheads and tanks is not to be less than:

$$t = 22,4 \cdot \sqrt{\frac{p}{G_{\text{perm}} \cdot f_a \cdot f_c + t_k}} \text{ mm}$$
a = shorter span of panel [m], respectively frame spacing a
b = longer span of panel in [m]
p = applicable design load
   = \( p_h \) on hull according to Section 3, B.1.
   = \( p_w \) on weather deck according to Section 3, B.3.
   = \( p_s \) on superstructures and deckhouses according to Section 3, B.4.
   = \( p_{ah} \) on accommodation decks according to Section 3, B.5.
   = \( p_{bh} \) on watertight bulkheads according to Section 3, B.6.
   = \( p_t \) in tanks according to Section 3, B.7.
\[ \sigma_{perm} = \frac{185}{k} \text{ [N/mm}^2\text{]} \]
k = material factor for steel materials according to Section 2, B. as well as for aluminum alloys according Section 2, C.6.
f_a = aspect ratio factor
   \[ = 0.54 + 0.23 \frac{b}{a} \text{ for } 1 \leq \frac{b}{a} \leq 2 \]
   \[ = 1 \text{ for } \frac{b}{a} > 2 \]
f_c = correction factor for plate panels with simple convex curvature according to B.12.3
f_k = corrosion allowance according to 1.2
2.3.2 Compliance with minimum thickness requirements according to 1.3 is always mandatory.

3. Structural members

3.1 General

The following formulae to determine the required section modulus and shear area apply to stiffeners, frames, floors, beams and girders. They are valid for stiffening members with webs either perpendicular to the plating or deviating not more than 15° from the perpendicular. In case this angle \( \alpha \) exceeds 15°, the required values are obtained by dividing the results of the following formulae by \( \cos \alpha \).

3.2 Section modulus

The section modulus \( W \) of a stiffening member required for support of the plating loaded with the design pressure is not to be less than:
\[ W = \frac{c \cdot p \cdot a \cdot \ell^2}{\sigma_{perm} \cdot f_{cs}} \text{ [cm}^3\text{]} \]
c = correction factor for boundary conditions
\[ = 83 \text{ for both ends constraint see B.12.6} \]
\[ = 125 \text{ for one or both ends simply supported, see B.12.6} \]
p = applicable design load [kN/m²] according to Section 3, B.
a = load span [m]
\( \ell \) = unsupported length of stiffener [m], see B.12.4 and B.12.5
\( f_{cs} \) = correction factor for plate panels with simple convex curvature according to B.12.3
\[ \sigma_{perm} \] = permissible stress
\[ = \frac{150}{k} \text{ [N/mm}^2\text{]} \]
k = material factor according to Section 2, B. and C.

3.3 Shear area

The shear area, i.e. the cross sectional area of the web of the stiffening member \( A \) is not to be less than:
\[ A = \frac{5 \cdot p \cdot a \cdot \ell}{\tau_{perm}} \text{ [cm}^2\text{]} \]
p, a, \( \ell \), as defined in 3.2
\( \tau_{perm} \) = permissible shear stress
\[ = \frac{100}{k} \text{ [N/mm}^2\text{]} \]

3.4 Brackets

Required scantlings for brackets are defined in B.12.7.

4. Permissible equivalent stress

4.1 The equivalent stress \( \sigma_v \) for hull structural members is to be determined according to:
\[ \sigma_v = \sqrt{\sigma_b^2 + 3 \cdot \tau^2} \text{ [N/mm}^2\text{]} \]
\( \sigma_b \) = bending stress [N/mm²]
\( \tau \) = shear stress [N/mm²]

4.2 The equivalent stress for metallic structures is not to exceed the following value:
\[ \sigma_v = \frac{190}{k} \text{ [N/mm}^2\text{]} \]
k = k or \( k_{al} \), material factor for steel or aluminium according to Section 2, B.1.2 or C.6.
5. **Pillars**

5.1 **General**

5.1.1 Structural members at heads and heels of pillars as well as substructures are to be constructed according to the forces they are subject to. Pillars shall rest on girders, floors or other pillars. Openings in webs of floors and girders below pillars are to be avoided. Where pillars on the inner bottom are not in way of intersections of floors and girders, partial floors or other structures are to be provided to support the load transmitted.

5.1.2 The equivalent stress for metallic structures is not to exceed the following value:

\[
\sigma_v = \frac{100}{k}
\]

5.1.3 Where possible, upper deck pillars shall be aligned with pillars below. stiffeners ensuring efficient load distribution are to be fitted at the ends of pillars.

5.1.4 Pillars in tanks are to be checked for tension. Tubular pillars are not permitted in tanks for flammable liquids.

5.2 **Definition of loads and geometric parameters**

\[
\begin{align*}
PS &= \text{pillar load [kN]} \\
P_L &= \text{load on decks [kN/m²]} \text{ according to Section 3, B.3. to B.5.} \\
A &= \text{load area for one pillar [m²]} \\
P_i &= \text{load from pillars located above the pillar considered [kN]} \\
\ell_S &= \text{length of pillar [cm]} \\
I_S &= A_S \cdot i_S^2 \\
&= \text{moment of inertia of the pillar [cm⁴] considering effective width} \\
A_S &= \text{sectional area of the pillar [cm²]} \\
i_S &= \text{radius of gyration of the pillar [cm]} \\
&= 0,25 \cdot d_S \text{ for solid pillars of circular cross section} \\
&= 0,25 \cdot \sqrt{d_a^2 + d_i^2} \\
d_S &= \text{pillar diameter of solid pillars [cm]} \\
d_a &= \text{outside diameter of tubular pillars [cm]} \\
d_i &= \text{inside diameter of pillar [cm]}
\end{align*}
\]

5.3 **Buckling criterion**

The chosen scantlings of a pillar have to meet the following buckling criterion:

\[
\frac{1,1 \cdot \sigma_x}{\kappa \cdot \sigma_{ki}} \leq 1
\]

\[
\sigma_x = \text{buckling stress in longitudinal direction of the pillar [N/mm²]}
\]

\[
\sigma_{ki} = \frac{\nu \cdot P_S \cdot 10}{A_S}
\]

\[
\nu = \text{ safety factor} = 1,50
\]

\[
\kappa = \frac{1}{\varphi + \sqrt{\varphi^2 - \lambda^2}}
\]

\[
\varphi = 0,5 \left(1 + n_p \cdot (\lambda - 0,2) + \lambda^2 \right)
\]

\[
n_p = \begin{cases} 0,34 & \text{for pipes and box sections} \\ 0,49 & \text{for open sections} \end{cases}
\]

\[
\lambda = \sqrt{\frac{R_{eh}}{\sigma_{ki}}}
\]

\[
R_{eh} = \text{minimum nominal upper yield stress [N/mm²] according to Section 2, B.1.1 and B.1.2}
\]

In case of aluminium alloy pillars \(R_{eh}\) is to be substituted by \(R_{p0,2}\) (see Section 2, C.6)

\[
\sigma_{ki} = \text{pillar buckling stress [N/mm²]}
\]

\[
\sigma_{ki} = \frac{\pi^2 \cdot E \cdot I_S}{I_S^2 \cdot k_S} A_S
\]

\[
E = \text{modulus of elasticity [N/mm²]}
\]

\[
k_S = 1,0 \text{ in general. For pillars which end supports can be considered as rigidly fixed, } k_S \text{ may be reduced accordingly}
\]

5.4 **Minimum wall thickness**

The wall thickness of tubular pillars which may be expected to be damaged during equipment handling, etc. is not to be less than:

\[
t_w = \begin{cases} 4,5 + 0,015 \cdot d_a & [\text{mm}] \\ 4,5 + 0,03 \cdot d_a & [\text{mm}] \end{cases}
\]

for \(d_a \leq 300 \text{ mm}\)

for \(d_a > 300 \text{ mm}\)

6. **Foundations for propulsion engines**

6.1 **General**

6.1.1 The following requirements apply to diesel engines, gears and generators.
6.1.2 The rigidity of the engine seating and the surrounding bottom structure must be adequate to keep the deformations of the system due to the loads within the permissible limits. In special cases, proof of deformations and stresses may be required.

6.2 Due regard is to be paid, at the initial design stage, to a good transmission of forces in transverse and longitudinal direction.

6.3 The foundation bolts for fastening the engine at the seating shall be spaced no more than $3 \times d$ apart from the longitudinal foundation girder. Where the distance of the foundation bolts from the longitudinal foundation girder is greater, proof of equivalence is to be provided.

d = diameter of the foundation bolts

6.4 In the whole speed range of main propulsion installations for continuous service resonance vibrations with inadmissible vibration amplitudes must not occur; if necessary structural variations have to be provided for avoiding resonance frequencies. Otherwise, a barred speed range has to be fixed. Within a range of $-10\%$ to $+5\%$ related to the rated speed no barred speed range is permitted. GL may require a vibration analysis and, if deemed necessary, vibration measurement.

6.5 Longitudinal girders

6.5.1 The thickness of longitudinal girders for internal combustion engines is not to be less than:

$$t = \left( \frac{P}{n \cdot e_1 \cdot c + G} \right) \cdot \frac{3.75}{\ell_m} \ [\text{mm}]$$

$$c = \frac{1}{0.025 \cdot \sqrt{P}}$$

$$0.2 \leq c \leq 0.5 \quad \text{for 4-stroke engines}$$

$$t_{\min} = 0.4 \cdot t_p \ [\text{mm}]$$

$$t_p = \text{thickness of top plate, see 6.5.3}$$

$$P = \text{rated driving power of the engine [kW]}$$

$$n = \text{rated speed at output [1/min]}$$

$$G = \text{weight of engine [kN]}$$

$$\ell_m = \text{bolted length of engine on foundation [m]}$$

$$e_1 = \text{distance of the longitudinal girders}$$

The web thickness of longitudinal girders for elastically mounted four-stroke internal combustion engines may be reduced to:

$$t' = 0.9 \cdot t$$

if two longitudinal girders are provided at each side of an internal combustion engine.

6.5.2 The thickness of the longitudinal girders for gears or generators is not to be less than:

$$t = \frac{P}{n \cdot e_1 \cdot \left( \frac{\ell_m}{3} + e_1 \right)} \ [\text{mm}]$$

$$P = \text{rated output of gear or generator [kW]}$$

$$e_1, \ell_m = \text{see 6.5.1}$$

6.5.3 The sizes of the top plate (width and thickness) shall be sufficient to attain efficient attachment and seating of the engine and – depending on seating height and type of engine – adequate transverse rigidity. The thickness of the top plate shall be:

$$t_p = 0.9 \cdot d \ [\text{mm}]$$

d = diameter of the foundation bolts [mm]

The cross sectional area of the top plate is not to be less than:

$$A_T = \begin{cases} \frac{P}{75} + 30 \ [\text{cm}^2] & \text{for } P \leq 750 \text{ kW} \\ \frac{P}{75} + 70 \ [\text{cm}^2] & \text{for } P > 750 \text{ kW} \end{cases}$$

$$P = \text{see 6.5.1}$$

Where twin engines are fitted, a continuous top plate is to be arranged in general if the engines are coupled to one propeller shaft.

6.5.4 Top plates are preferably to be connected to longitudinal and transverse girders thicker than approx. 15 mm by means of a double bevel butt joint (K butt joint).

6.6 Transverse support of longitudinal girders

6.6.1 The sectional modulus and the cross sectional area of the floor plates between longitudinal girders are not to be less than:

$$W = \left( \frac{120 \cdot P}{n} + e_1 \cdot G \right) \frac{7 \cdot a}{\ell_m} \ [\text{cm}^3]$$

$$A_s = \frac{0.35 \cdot a \cdot G}{\ell_m} \ [\text{cm}^2]$$
a = distance of the floor plates [m]
For all other parameters see 6.5.1

6.6.2 The longitudinal girders of the engine seating are to be supported transversely by means of web frames or wing bulkheads.

7. Keel and keel attachment scantling determination

7.1 Permissible stresses
Permissible stresses for all metal components of a keel arrangement subject to the loads as specified in Section 3, C.3, are not to exceed values as specified in Table 5.3 and Table 5.4.

Table 5.3 Permissible stresses for keel structural elements not subjected to local stress concentration

<table>
<thead>
<tr>
<th></th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ, σν</td>
<td>120/k</td>
<td>120/k</td>
<td>150/k</td>
</tr>
<tr>
<td>τ</td>
<td>80/k</td>
<td>80/k</td>
<td>90/k</td>
</tr>
</tbody>
</table>

Table 5.4 Permissible stresses for keel structural elements subjected to local stress concentration (e.g. threads, etc.)

<table>
<thead>
<tr>
<th></th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ, σν</td>
<td>110/k</td>
<td>110/k</td>
<td>140/k</td>
</tr>
<tr>
<td>τ</td>
<td>70/k</td>
<td>70/k</td>
<td>80/k</td>
</tr>
</tbody>
</table>

LC1 to LC3 are defined in Section 3, C.2.

σ-Stresses are axial stresses generated from tension, compression and bending. τ-Stresses are generated from shear forces and torque.

Von Mises stresses σ_v are to be calculated as follows:

$$\sigma_v = \sqrt{\left(\sigma^2 + 3 \cdot \tau^2\right)}$$

7.1.1 Material factor k
The material factor k for steels and aluminium alloys for the use in keel design has to be determined as follows:

$$k = \left(\frac{235}{R_{\text{eH}}}\right)^{0.75} \text{ for } R_{\text{eH}} > 235 \text{ N/mm}^2$$

$$k = \frac{235}{R_{\text{eH}}} \text{ for } R_{\text{eH}} \leq 235 \text{ N/mm}^2$$

For austenitic steels, R_p0.2 is to be taken for R_{eH}.

7.2 Fatigue assessment
A separate fatigue assessment is required, in particular for welded constructions. Relate to Annex A.

8. Rudder scantlings
Metal parts of the rudder shall be treated in accordance with allowable stresses defined in 7.1 with LC1 applicable.

For fibrous composite construction, allowable strains in shaft and blade may not exceed limits as per definition in Section 4.
Section 6

Design and Scantlings for Steel Structures of Yachts L ≥ 48 m

A. General

1. Scope

The following references to GL Rules applicable for scantling determination of the hull structures of sailing yachts with \( L > 48 \) m, see C. Regarding corrosion allowances and minimum thickness of plating the requirements specified in C.1. and C.2. are applicable.

B. Materials

See Section 2.

C. Scantlings

1. Corrosion allowances

The following, reduced corrosion allowances may be applied for yachts, if special care for maintenance and special attention for measures of corrosion protection can be assumed.

1.1 Steel

The scantlings require the following allowances \( t_k \) to the theoretical, rounded-off plate thickness:

- \( t_k = 0,5 \) mm in general
- \( t_k = 0,7 \) mm for lubrication oil, gas oil or equivalent tanks
- \( t_k = 1,0 \) mm for water ballast and heavy oil tanks

For special applications \( t_k \) shall be agreed with GL.

For all elements of the yacht’s structure which form a boundary of tanks, the \( t_k \) values for tanks have to be considered.

1.2 Aluminium alloys

If the measures for corrosion protection described in Section 2, E. are fully applied, the corrosion allowance \( t_k \) can be assumed as 0 for the types of aluminium alloys defined in Section 2, C.3. and C.4. In any way \( t_k \) shall not be less than the fabrication tolerances, see GL Rules for Non-Ferrous Metals (II-1-3), Section 1.

2. Minimum thickness

The minimum thickness requirements of the plating of different elements of the hull structure are summarized in Table 6.1.

For comparison the table indicates references to the GL Rules for Hull Structures (I-1-1).

<table>
<thead>
<tr>
<th>Elements of the hull structure</th>
<th>Minimum thickness ( t_{\text{min}} ) of plating [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Designation</strong></td>
<td><strong>Reference</strong></td>
</tr>
<tr>
<td>Brackets</td>
<td>Section 3, D.2.2</td>
</tr>
<tr>
<td>Bottom</td>
<td>Section 6, B.3.1</td>
</tr>
<tr>
<td>Flat plate keel</td>
<td>Section 6, B.5.1</td>
</tr>
<tr>
<td>Side shell</td>
<td>Section 6, C.2.</td>
</tr>
<tr>
<td>Strength deck for 0,4 L amidships outside line of openings</td>
<td>Section 7, A.6.</td>
</tr>
<tr>
<td>Strength deck inside line of openings and 0,1 L from the ends</td>
<td>Section 7, A.7.</td>
</tr>
<tr>
<td>Lower decks (2nd deck)</td>
<td>Section 7, B.1.1</td>
</tr>
<tr>
<td></td>
<td>Formulae for yachts</td>
</tr>
<tr>
<td></td>
<td>( 5,5 )</td>
</tr>
<tr>
<td></td>
<td>( 0,9 \cdot \sqrt{L \cdot k} )</td>
</tr>
<tr>
<td></td>
<td>( t_{\text{min}} ) (bottom) + 2,0 mm for 0,7 L midships and in way of engine seating; ( t_{\text{min}} ) (bottom) otherwise</td>
</tr>
<tr>
<td></td>
<td>( 0,8 \cdot \sqrt{L \cdot k} )</td>
</tr>
<tr>
<td></td>
<td>( (3,5 + 0,05 \cdot L) \cdot \sqrt{k} )</td>
</tr>
<tr>
<td></td>
<td>( (4,5 + 0,02 \cdot L) \cdot \sqrt{k} )</td>
</tr>
<tr>
<td></td>
<td>( (4,5 + 0,02 \cdot L) \cdot \sqrt{k} )</td>
</tr>
<tr>
<td>Elements of the hull structure</td>
<td>Reference ¹</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Other lower decks</td>
<td>Reference ¹</td>
</tr>
<tr>
<td>Floor plates in the peaks</td>
<td>Section 8, A.1.2.3</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Web of single bottom centre girder</td>
<td>Section 8, A.2.2.1</td>
</tr>
<tr>
<td>Web of single bottom side girder</td>
<td>Section 8, A.2.2.2</td>
</tr>
<tr>
<td>Double bottom longitudinal girders</td>
<td>Section 8, B.7.5.2</td>
</tr>
<tr>
<td>Web frames in machinery spaces</td>
<td>Section 9, A.6.2.1</td>
</tr>
<tr>
<td>Bulkhead plating</td>
<td>Section 11, B.2.1</td>
</tr>
<tr>
<td>Internal wall plating</td>
<td>–</td>
</tr>
<tr>
<td>Tank structures</td>
<td>Section 12, A.7.1</td>
</tr>
<tr>
<td>Rudder horn plating</td>
<td>Section 13, C.4.5</td>
</tr>
<tr>
<td>Webs of rudders</td>
<td>Section 14, E.2.3</td>
</tr>
<tr>
<td>Non-effective superstructure side walls</td>
<td>Section 16, B.1.1</td>
</tr>
<tr>
<td>Non-effective superstructure deck</td>
<td>Section 16, B.2.1</td>
</tr>
<tr>
<td>Superstructure end bulkheads and deckhouse walls/lowest tier</td>
<td>Section 16, C.3.2</td>
</tr>
<tr>
<td>Superstructure end bulkheads and deckhouse walls/upper tier</td>
<td>Section 16, C.3.2</td>
</tr>
<tr>
<td>Short deckhouse deck</td>
<td>Section 16, D.1</td>
</tr>
<tr>
<td>Hatchway coamings</td>
<td>Section 17, C.2.1</td>
</tr>
<tr>
<td>Steel hatch covers</td>
<td>Section 17, B.5.1.1</td>
</tr>
</tbody>
</table>

¹ in GL Rules for Hull Structures (I-1-1)
Section 7

Chainplates and Propeller Brackets

A. General

The following specifies scantling requirements for the above elements and their structural attachment to the yacht’s hull.

B. Chainplates and Substructures

1. Design loads

Where no other indications are available, the dimensioning load will be equal to the breaking load of the attached shrouds and stays. If there are two shrouds attached to a chainplate, the dimensioning load for the chainplate is

\[ F = 1.0 \times \text{breaking load of the stronger shroud} + 0.5 \times \text{breaking load of the weaker shroud} \ [\text{kN}] \]

2. Permissible stresses

For dimensioning of chainplates made of metallic materials the following permissible stresses are to be complied with:

- permissible bearing stress between chainplate and pin:

\[ \sigma_{\text{LL, perm}} = \frac{R_{\text{eh}} + R_m}{2} \ [\text{N/mm}^2] \]

- for tension and shear loading:

\[ \sigma_{\text{perm}} = \frac{R_{\text{eh}}}{2} \ [\text{N/mm}^2] \]
\[ \tau = \frac{R_{\text{eh}}}{\sqrt{3}} \ [\text{N/mm}^2] \]

\( R_{\text{eh}} \) is the steel’s minimum nominal upper yield point [N/mm²] as defined in Section 2, B. In case of aluminium alloys \( R_{\text{eh}} \) is to be replaced by \( R_{\text{p}0.2} \) i.e. the 0.2 % proof stress [N/mm²] as defined in Section 2, C.

3. Determination of chainplate parameters

3.1 Metallic chainplates

Determination of geometry and thickness of a metallic chainplate according to Fig. 7.1.

\[
\begin{align*}
\alpha_{\text{min}} &= \frac{F}{2 \cdot t \cdot \sigma_{\text{perm}}} + \frac{2}{3} d_L \ [\text{mm}] \\
\varepsilon_{\text{min}} &= \frac{F}{2 \cdot t \cdot \sigma_{\text{perm}}} + \frac{1}{3} d_L \ [\text{mm}]
\end{align*}
\]

d_L = \text{pin hole diameter} \ [\text{mm}]

Thereby it is assumed that the gap between bearing hole and pin is smaller than \( 0.1 \cdot d_L \). Also the bearing stress limit according to 2. must be observed.

3.2 Metallic chainplate structure

The dimensioning principles, i.e. design load and permissible stress for chainplates of metallic materials as outlined above are to be applied analogously to the metallic chainplate substructure, e.g. tie rods, etc.

3.3 Chainplates of composite materials

Regarding chainplate components made of composite materials, e.g. carbon fiber tapes, and composite structures to which chainplates are attached, e.g. FRP bulkheads, dimensioning is to be carried out as follows.

3.3.1 The relevant stress in the composite component, e.g. tension or shear, is to be calculated applying the design load according to 1.

3.3.2 The permissible stress shall be less than or equal to the ultimate stress of the composite component divided by 1.6.

4. Structural members in way of chainplates

Scantlings of structural members in way of chainplates must ensure sufficient strength and rigidity of the hull under the consideration of the design loads defined in 1.
C. Propeller Brackets

1. Arrangement

Fixed propeller brackets can be of double or single strut type. Should the propulsion unit be retractable, other arrangements guiding and supporting the propeller are possible.

Propeller brackets and their structural foundation are to be designed to cope for the following typical aspects:
- Hydrodynamic forces generated by propeller
- High magnitude of cyclic loadings
- Mass imbalance of propeller and/or shaft
- Cases like catching a rope
- Stiffness requirements for the propulsion unit
- Offset if propeller is not mounted directly behind shaft bracket

2. Metallic double strut brackets

2.1 The strut axes should intersect in the axis of the propeller shaft as far as practicable. The angle between two struts shall be in range from 50° to 120° which differs from the angle included between propeller blades. Where 3- or 5-bladed propellers are fitted, an approximately 90° angle is recommended.

Where 4-bladed propellers are fitted, the angle should be approximately 70° or 110°. The axes of the arms should intersect in the axis of the propeller shaft.

Exceptions to this will be considered by GL on a case-by-case basis.

The struts are to be extended through the shell plating and are to be attached in an efficient manner to the frames and plate floors respectively. The construction in way of the shell is to be carried out with special care.

2.2 In general, the scantlings of solid struts can be determined as outlined below depending on required shaft diameter $d_s$:

- strut thickness $0,40 d_s$
- cross-sectional area $0,40 d_s^2$ in propeller bracket
- length of boss $2,5 d_{sa}$
- wall thickness of boss $0,25 d_s$

$d_{sa} = \text{as-built diameter}$

$$d_s = 95 \cdot \left( \frac{P_w \cdot C_w}{n} \right)^{1/3}$$

$$C_w = \frac{560}{160 + R_m}$$

$R_m = \text{tensile strength of the strut material [N/mm}^2]$\]

$P_w = \text{single engine output [kW]}$

$n = \text{shaft revolutions [min}^{-1}])$

Based on further details other scantling calculations can be accepted as agreed by GL.

2.3 Propeller brackets and shaft bossings of welded construction are to have the same strength as solid ones according to 2. The thickness of plating shall not be less than 0,1 $d_s$.

3. Metallic single strut brackets

3.1 For single strut propeller brackets a strength, vibration and fatigue analysis shall be carried out, should the scantlings deviate from the ones defined in 3.2.

3.2 The section modulus of the arm of hull structural steel at its clamped support (without taking into account possible rounding) is to be determined according to the following formula:

$$W_1 = 0,0002 \cdot d_s^3 \cdot k \ [cm^3]$$

$k = \text{material factor according Section 2, B.}$

The section modulus at the boss, above any curvature, $(W_2)$ may not be less than:

$$W_2 = 0,00014 \cdot d_s^3 \cdot k \ [cm^3]$$

Fig. 7.2

The section moduli apply to an arm length $L' = 11 \cdot d_s$ and shorter. For longer arms, the section modulus is to be increased in proportion with the length.

4. Other propeller bracket arrangements

4.1 Other propeller bracket arrangements are to be designed accordingly, but need to be considered case-by-case.

4.2 For alternative determination of the propeller bracket scantlings, GL provides guidance on design loads.

4.3 Bending stress for metallic shaft brackets are not to exceed:

$$\sigma_{b\max} = \frac{90}{k}$$

$k = \text{material factor according Section 2, B. and C.}$
4.4 Scantlings for composite shaft brackets
Permissible material stresses/strains and safety factors for components of propeller brackets and associated structures subject to the loads as specified in 4.2 are defined in Section 4. C.8., where these permissible strains/stresses must be 1.2 times lower than those defined and safety factors 1.2 times higher than those defined.
Annex A

Keel Fatigue Assessment

Introduction:

The following has been condensed from GL Rules for Hull Structures (I-1-1), Section 20. This Section has been modified to be applicable to fatigue assessment of Racing Yacht keels.

At this stage of development this assessment is considered valid for racing yachts of any length. It might prove that generating individual cycling regimes like described in this methodology might not be necessary. In order to at a later stage simplify the process of generating cycling regimes it might show that a unit regime might suffice with appropriate reliability.

A separate spread sheet containing the major computations according to this assessment can be obtained from GL.

Preface

The proof of sufficient fatigue strength, i.e. the strength against crack initiation under dynamic loads during operation, is useful for judging and reducing the probability of crack initiation of structural members already during the design stage.

Due to the randomness of the load process, the spreading of material properties and fabrication factors and to effects of ageing, crack initiation cannot be completely excluded during later operation. Therefore among other things periodical surveys are necessary.

Fatigue strength of welded metal connections is primarily a function of the weld category (“FAT-class”) and the quality of the welding performance including its post-treatment. Fatigue strength of welded details is considered more or less independent from the mechanical basic strength of the material. Thus, it is of great importance that the weld provides low stress concentrations and is of a high quality, so that the use of very high strength steel is beneficial.

A. General

1. Definitions

\[ \Delta \sigma = \text{applied stress range} \left( \sigma_{\text{max}} - \sigma_{\text{min}} \right) \quad \text{[N/mm}^2\text{]}, \text{see also Fig. A.1} \]

\[ \sigma_{\text{max}} = \text{maximum upper stress of a stress cycle} \quad \text{[N/mm}^2\text{]} \]

\[ \sigma_{\text{min}} = \text{maximum lower stress of a stress cycle} \quad \text{[N/mm}^2\text{]} \]

\[ \Delta \sigma_{\text{max}} = \text{applied peak stress range within a stress range spectrum} \quad \text{[N/mm}^2\text{]} \]

\[ \sigma_{\text{m}} = \text{mean stress} \left( \sigma_{\text{max}}/2 + \sigma_{\text{min}}/2 \right) \quad \text{[N/mm}^2\text{]} \]

\[ \Delta \sigma_{\text{p}} = \text{permissible stress range} \quad \text{[N/mm}^2\text{]} \]

\[ \Delta_{\tau} = \text{Corresponding range for shear stress} \quad \text{[N/mm}^2\text{]} \]

\[ n = \text{number of applied stress cycles} \]

\[ N = \text{number of endured stress cycles according to S-N curve (= endured stress cycles under constant amplitude loading)} \]

\[ \Delta \sigma_{\text{R}} = \text{fatigue strength reference value of S-N curve at } 2 \times 10^6 \text{ cycles of stress range} \quad \text{[N/mm}^2\text{]} \quad (= \text{FAT class according to Table A.4}) \]

\[ f_{\text{m}} = \text{correction factor for material effect} \]

\[ f_{\text{R}} = \text{correction factor for mean stress effect} \]

\[ f_{\text{w}} = \text{correction factor for weld shape effect} \]

\[ f_{i} = \text{correction factor for importance of structural element} \]
f_s = additional correction factor for structural stress analysis
f_n = factor considering stress spectrum and number of cycles for calculation of permissible stress range
Δσ_{Rc} = corrected fatigue strength reference value of S-N curve at 2·10^6 stress cycles [N/mm²]
D = cumulative damage ratio

2. Scope

2.1 A fatigue strength analysis is to be performed for structures which are predominantly subjected to cyclic loads. The notched details i.e. the welded joints as well as notches at free plate edges are to be considered individually. The fatigue strength assessment is to be carried out on the basis of a cumulative damage ratio, see B.2.1.

2.2 No fatigue stress analysis is required to be carried out, if the peak stress range due to dynamic loads defined further below fulfils the following condition:

\[ \Delta\sigma_{\text{max}} \leq 2.5 \Delta\sigma_{R} \]

where:

\[ \Delta\sigma_{\text{max}} = 2 \cdot \Delta\sigma_{n} \]
\[ \Delta\sigma_{n} \text{ from 2.4.5} \]

2.3 The rules are applicable to constructions made of normal and higher-strength hull structural steels according to Section 2, B. as well as aluminium alloys. Other materials such as cast steel can be treated in an analogous manner by using appropriate design S-N curves.

Low cycle fatigue problems in connection with extensive cyclic yielding have to be specially considered. When applying the following rules, the calculated nominal stress range should not exceed 1.5 times the minimum nominal upper yield point. In special cases the fatigue strength analysis may be performed by considering the local elasto-plastic stresses, the latter which is outside the scope of this Section.

2.4 Load spectrum / cycling regime

2.4.1 General

From the dynamic motions of racing yachts, the dynamic stress amplitudes in a keel component have to be derived. These stress amplitudes vary with the characteristic motions of a yacht.

These Guidelines are limited to evaluating only motions that excite the keel in transverse bending. This loading phenomenon is considered to highly contribute to fatigue-relevant loading. Other loading scenarios of a keel on the remaining 4 degrees of freedom should not be ignored but will not be addressed within these guidelines particularly.

The typical characteristic motions of keel transverse bending are divided in two groups:

- sailing (heeled) in seaways underlying vertical acceleration additional to gravity, see 2.4.2
- change of tack, see 2.4.3

Under this scope, racing yachts with keels fixed in centre-plane will be treated different from yachts with cantiing keels.

This cycling regime which is to be expected during the service life of a racing yacht keel will be described by a characteristic spectrum. This spectrum for racing yacht keels differs from common spectra used for ships in seaway condition or the ones used for more regular excitments like engine vibrations.

The characteristic cycling regime is intended to provide coverage of min. 60000 miles (depending on boat size) under random sea conditions. The dynamic loadings cumulating to this spectrum are derived from wave encounters resulting in amplified gravitational effects.

2.4.2 Design life / wave encounters

In order to establish the number of cycles and a mileage, a “Design Life” is defined including a percentage of this value being spent at sea.

“Design Life” is an expression representing a theoretical time span in which fatigue degradation is not leading to premature failure, if the provisions of these guidelines are being followed.

A default value of this design life is 5 years with a fraction of 15% spend at sea, or the pertinent mileage.

Within these guidelines, the design life has a default consistency. It is divided in four characteristic headings, where a quarter of the life is absorbed under each heading. See Table A.1.

<table>
<thead>
<tr>
<th>Table A.1</th>
<th>Headings in life time; TWA = true wind angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heading</td>
<td>of Design Lifetime</td>
</tr>
<tr>
<td>Upwind 45° TWA</td>
<td>25%</td>
</tr>
<tr>
<td>Beam reach 90° TWA</td>
<td>25%</td>
</tr>
<tr>
<td>Broad reach 135° TWA</td>
<td>25%</td>
</tr>
<tr>
<td>Running 180° TWA</td>
<td>25%</td>
</tr>
</tbody>
</table>

Of this total time, the boat is expected to experience certain sea state conditions, defined by a wave
length, each with a default share of the total time, as shown in Table A.2:

<table>
<thead>
<tr>
<th>Sea State</th>
<th>of Design Lifetime</th>
<th>typical heel angle</th>
<th>wave length λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme Condition</td>
<td>1 %</td>
<td>45°</td>
<td>3 ·LWL</td>
</tr>
<tr>
<td>Severe Condition</td>
<td>5 %</td>
<td>35°</td>
<td>2 ·LWL</td>
</tr>
<tr>
<td>Regular Condition</td>
<td>10 %</td>
<td>30°</td>
<td>1 ·LWL</td>
</tr>
<tr>
<td>Moderate Conditions</td>
<td>25 %</td>
<td>25°</td>
<td>0.75 ·LWL</td>
</tr>
<tr>
<td>Light Conditions</td>
<td>59 %</td>
<td>15°</td>
<td>0.5 ·LWL</td>
</tr>
</tbody>
</table>

For each sea state, the boat is dedicated a certain heel angle under sail, as per Table A.2. For each combination heading/sea state, the encounter between boat and wave is determined using the following parameters:

- **Wave period:**
  \[ T_w = \sqrt{\frac{2 \cdot \pi \cdot \lambda}{9.81}} \quad [s] \]

- **Wave angular frequency:**
  \[ \omega = \frac{2 \cdot \pi}{T_w} \quad [rad/s] \]

The **angular frequency of encounter** between boat and wave:

\[ \omega_e = \omega - \left( \frac{\omega^2}{9.81} \cdot \frac{v_0}{1.94} \cdot \cos(180 - \phi) \right) \]

\[ \phi = \text{heading or TWA} \quad [\text{deg}] \]

\[ v_0 = \text{boat design speed} \quad [\text{kn}] \]

The **period of encounter** between boat and wave:

\[ T_e = \frac{2 \cdot \pi}{\omega_e} \quad [s] \]

The total number of cycles for each case heading / sea state can be determined by dividing the time spent by the period of encounter \( T_e \).

### 2.4.2.1 Heave accelerations

In order to determine the pertinent heave accelerations of the boat for each of the case heading/sea state, the vertical acceleration of the wave surface is determined for each wave and amplified with a coefficient \( c_a \) as shown in Table A.3. The latter is to estimate the typical response of boats on waves of a certain length.

The wave height [m] of the regular design wave is approximated using a 4th grade polynomial:

\[ H = -0.00042 \cdot T_w^4 + 0.016 \cdot T_w^3 - 0.0017 \cdot T_w^2 + 0.11 \cdot T_w - 0.06 \]

The vertical surface acceleration is determined as follows:

\[ a_{vw} = \frac{2 \cdot \omega_e^2}{H} \quad [m/s^2] \]

<table>
<thead>
<tr>
<th>Sea state</th>
<th>Amplifying coefficient ( c_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>1,2</td>
</tr>
<tr>
<td>Severe</td>
<td>1,0</td>
</tr>
<tr>
<td>Regular</td>
<td>0,8</td>
</tr>
<tr>
<td>Moderate</td>
<td>0,6</td>
</tr>
<tr>
<td>Light</td>
<td>0,4</td>
</tr>
</tbody>
</table>

The vertical acceleration amplitude for the purpose of estimating gravitational loads on the keel is calculated as follows:

\[ a_v = a_{vw} \cdot c_a \quad [-] \]

### 2.4.2.2 Probability evaluation

In a next step, a probability evaluation is carried out; the purpose of which is to account for the fact that any experienced sea state is not of regular character. Within a given case heading/sea state, 1/100th, 1/10th acceleration amplitudes will be obtained by factoring, on the basis of the \((1+\log_{e}N)\) method.

Individual accelerations and pertinent number of cycles are derived for each case of heading/ wave height/ sea state extremity/ probability evaluation.

### 2.4.3 Design life - full reversal loads

The design life of a keel includes also full reversal loads. By nature these loads are different from the loads experienced by wave encounters as per 2.4.2, as they represent full reversal, occurring e.g. by the change of tack of a boat.

For the design life as per definition in 2.4.2, a number of 30 changes of tack per day are default, using...
the heel angles from Table A.2 as full reversal amplitude.

### 2.4.4 Stress range

In order to transfer the cycling regime defined in 2.4 into a stress range spectrum required for the fatigue analysis, the pertinent stress ranges $\Delta \sigma_i$ can be calculated using the resulting keel angle to vertical and the resulting gravitational forces due to the defined accelerations and the basic static nominal stress calculated from Load case 1 (90 degree heel).

For cases “Sailing” as per 2.4.2, the stress range values $\Delta \sigma_i$ are derived as follows:

$$\Delta \sigma_i = \sigma_n \cdot \sin(\alpha + \delta) \cdot \left( 1 + \frac{1}{a_v + 1} \right)$$

For cases “Knock Down” and “Tack/Jibe” as per 2.4.3., the stress range values $\Delta \sigma_i$ are derived as follows:

$$\Delta \sigma_i = \sigma_n \cdot 2 \cdot \sin(\alpha + \delta) \cdot (1 + a_{dy})$$

Where:

- $\alpha$ = keel angle to vertical [deg]
- $\delta$ = maximum canting angle to centre plane of yacht, for fixed keel yachts = 0 [deg]
- $\sigma_n$ = nominal stress from static load case LC1 at location of interest [MPa]
- $a_v$ = dynamic acceleration offset on gravity [g]

For each stress range $\Delta \sigma_i$ a value $N_i$ will be determined (ultimate number of cycles) according to a standard Wöhler curve. The ratio between the defined cycles $n_i$ and the ultimate cycles $N_i$ will be called partial fatigue damage. Cumulating this ratio across the spectrum results in the overall fatigue damage ratio as defined in B.2.

### 2.5 Combined stresses

The fatigue strength evaluation needs to be carried out at all locations subject to high stressing.

Due to keel bending, not only tensile/compressive stresses occur, but also those combined with shear stresses, e.g. near the outboard junction of a shear web and plating.

In those cases, the principle stress shall be determined and the resulting value is subject to fatigue assessment, see B.1.4.

For locations with a governing shear stress, alternative FAT class values are to be adopted as per definition in B.1.6.

### 2.6 The fatigue strength analysis is, depending on the structural detail considered, and based on one of the following types of stress:

- For notches of free plate edges the notch stress $\sigma_k$, determined for linear-elastic material behaviour, is relevant, which can normally be calculated from a nominal stress $\sigma_n$ and a theoretical stress concentration factor $K_t$. Values for $K_t$ are given in the GL Rules for Hull Structures (I-1-1), Section 3, Fig. 3.9 and 3.10 for different types of cut-outs. The fatigue strength is determined by the FAT class ($\Delta \sigma_R$) according to Table A.4, type E2 and E3

- For welded joints the fatigue strength analysis is normally based on the nominal stress $\sigma_n$ at the structural detail considered and on an appropriate detail classification as given in Table A.4, which defines the FAT class ($\Delta \sigma_R$).

- For those welded joints, for which the detail classification is not possible or additional stresses occur, which are not or not adequately considered by the detail classification, the fatigue strength analysis may be performed on the basis of the structural stress $\sigma_s$ in accordance with C.

### 3. Quality requirements (fabrication tolerances)

#### 3.1 The detail classification of the different welded joints as given in Table A.4 is based on the assumption that the fabrication of the structural detail or welded joint, respectively, corresponds in regard to external defects at least to quality group B according to DIN EN ISO 5817 and in regard to internal defects at least to quality group C. Further information about the tolerances can also be found in the GL Rules for Design, Fabrication and Inspection of Welded Joints (II-3-2).

#### 3.2 Relevant information has to be included in the manufacturing document for fabrication. If it is not possible to comply with the tolerances given in the standards, this has to be accounted for when designing the structural details or welded joints, respectively. In special cases an improved manufacture as stated in 3.1 may be required, e.g. stricter tolerances or improved weld shapes, see also B.3.2.4.

#### 3.3 The following stress increase factors $k_m$ for considering significant influence of axial and angular misalignment are already included in the fatigue strength reference values $\Delta \sigma_R$ (Table A.4):

$$k_m = \begin{cases} 1,15 & \text{butt welds (corresponding type A1, A2, A11)} \\ 1,30 & \text{butt welds (corresponding type A3–A10)} \\ 1,45 & \text{cruciform joints (corresponding type D1–D5)} \end{cases}$$
= 1.25 fillet welds on one plate surface
(corresponding type C7, C8)

Other additional stresses need to be considered separately.

B. Fatigue Strength Analysis for Free Plate Edges and for Welded Joints Using Detail Classification

1. Definition of nominal stress and detail classification for welded joints

1.1 Corresponding to their notch effect, welded joints are normally classified into detail categories considering particulars in geometry and fabrication, including subsequent quality control, and definition of nominal stress. Table A.4 shows the detail classification based on recommendations of the International Institute of Welding (IIW) giving the FAT class \( \Delta \sigma_R \) for structures made of steel or aluminium alloys (Al).

In Table A.4 \( \Delta \sigma_R \)-values for steel are given for some intersections of longitudinal frames of different shape and webs, which can be used for the assessment of the longitudinal stresses.

It has to be noted that some influence parameters cannot be considered by the detail classification and that a large scatter of fatigue strength has therefore to be expected.

1.2 Details which are not contained in Table A.4 may be classified either on the basis of local stresses in accordance with C. or, else, by reference to published experimental work or by carrying out special fatigue tests, assuming a sufficiently high confidence level (see 3.1) and taking into account the correction factors as given in C.4.

1.3 Regarding the definition of nominal stress, the arrows in Table A.4 indicate the location and direction of the stress for which the stress range is to be calculated. The potential crack location is also shown in Table A.4.

1.4 Depending on this crack location, the nominal stress range has to be determined by using either the cross sectional area of the parent metal or the weld throat thickness, respectively. Bending stresses in plate and shell structures have to be incorporated into the nominal stress, taking the nominal bending stress acting at the location of crack initiation.

Note

The factor \( K_s \) for the stress increase at transverse butt welds between plates of different thickness (see type A5 in Table A.4) can be estimated in a first approximation as follows:

\[
K_s = \frac{t_2}{t_1}
\]

\( t_1 = \) smaller plate thickness

\( t_2 = \) larger plate thickness

Additional stress concentrations which are not characteristic of the FAT class itself, e.g. due to cut-outs in the neighbourhood of the detail, have also to be incorporated into the nominal stress.

1.5 In the case of combined normal and shear stress the relevant stress range is to be taken as the range of the principal stress at the potential crack location which acts approximately perpendicular (within \( \pm 45^\circ \)) to the crack front as shown in Table A.4 as long as it is larger than the individual stress components.

1.6 Where solely shear stresses are acting the largest principal stress \( \sigma_1 = \tau \) may be used in combination with the relevant FAT class.

2. Permissible stress range for the cumulative damage ratio

2.1 If the fatigue strength analysis is based on the calculation of the cumulative damage ratio, the stress range spectrum expected during the envisaged service life is to be established (see A.2.4) and the cumulative damage ratio \( D \) is to be calculated as follows:

\[
D = \sum_{i=1}^{I} \left( \frac{n_i}{N_i} \right)
\]

\( I = \) total number of blocks of the stress range spectrum for summation

\( n_i = \) number of stress cycles in block \( i \)

\( N_i = \) number of endured stress cycles determined from the corrected design S-N curve (see 3.) taking \( \Delta \sigma = \Delta \sigma_i \)

\( \Delta \sigma_i = \) stress range of block \( i \)

To achieve an acceptable high fatigue life, the cumulative damage ratio should not exceed \( D = 1 \).

3. Design S-N curves

3.1 Description of the design S-N curves

3.1.1 The design S-N curves for the calculation of the cumulative damage ratio according to 2.1 are shown in Fig. A.2 for welded joints at steel and in
Fig. A.3 for notches at plate edges of steel plates. For aluminium alloys (Al) corresponding S-N curves apply with reduced reference values of the S-N curves (FAT classes) acc. to Table A.4. The S-N curves represent the lower limit of the scatter band of 95 % of all test results available (corresponding to 97.5 % survival probability) considering further detrimental effects in large structures.

To account for different influence factors, the design S-N curves have to be corrected according to 3.2.

3.1.2 The S-N curves represent section-wise linear relationships between $\log(\Delta \sigma)$ and $\log(N)$:

$$\log(N) = 7 + m_0 \cdot \log(\frac{\Delta \sigma_{R}}{\Delta \sigma}) - \frac{0.69897}{m_0}$$

$m_0 = 3$ for welded joints

$= 3.5 - 5$ for free plate edges (see Fig A.3)

The S-N curve for FAT class 160 forms the upper limit for the S-N curves of free edges of steel plates with detail categories 100 – 150 in the range of low stress cycles ($< 10^7$), see Fig. A.3. The same applies accordingly to FAT classes 32 – 40 of aluminium alloys with an upper limit of FAT 71; see type E1 in Table A.4.

Fig. A.2 S-N curves for welded joints in steel

Fig. A.3 S-N curves for notches at plate edges of steel plates
3.2 Correction of the reference value of the design S-N curve

3.2.1 A correction of the reference value of the S-N curve (FAT class) is required to account for additional influence factors on fatigue strength as follows:

\[ \Delta \sigma_{Rc} = f_m \cdot f_R \cdot f_w \cdot f_i \cdot \Delta \sigma_R \]

where \( f_m, f_R, f_w, f_i \) defined in 3.2.2 – 3.2.5

For the description of the corrected design S-N curve, the formulae given in 3.1.2 may be used by replacing \( \Delta \sigma_R \) by \( \Delta \sigma_{Rc} \).

3.2.2 Material effect (\( f_m \))

For welded joints it is generally assumed that the fatigue strength is independent of steel strength, i.e.:

\[ f_m = 1,0 \]

For free edges at steel plates the effect of the material's yield point is accounted for as follows:

\[ f_m = 1 + \frac{R_{eH} - 235}{1200} \]

\( R_{eH} \) = minimum nominal upper yield point of the steel [N/mm²]

\( R_{eH} \leq 390 \text{ N/mm}^2 \) *

* Guidance note: The limitation originates from the use of ship building steels with yield strength of 390N/mm² and below. Without further proof, this limit applies also for higher strength steels used for racing yacht keel construction.

This correction is leading to over-optimistic life cycle predictions when used with yield strengths exceeding this value. Should higher strength steels be used, either the limit of 390 N/mm² shall be used or for a more individual evaluation fatigue life data shall be supplied for the relevant material.

For aluminium alloys, \( f_m = 1 \) generally applies.

3.2.3 Effect of mean stress (\( f_R \))

In a conservative approach, the stress cycling in racing yacht keels is considered mainly to occur as pulsating tensile stress.

Thus, the correction factor is calculated as follows:

\[ f_R = 1 \]

3.2.4 Effect of weld shape (\( f_w \))

In normal cases:

\[ f_w = 1,0 \]

A factor \( f_w > 1,0 \) applies for welds treated e.g. by grinding. Grinding removes surface defects such as slag inclusions, porosity and crack-like undercuts, to achieve a smooth transition from the weld to the base material. Final grinding shall be performed transversely to the weld direction. The depth should be about 0,5 mm larger than the depth of visible undercuts.

For ground weld toes of fillet and K-butt welds machined by:

- disc grinder: \( f_w = 1,15 \)
- burr grinder: \( f_w = 1,30 \)

Premise for this is that root and internal failures can be excluded. Application of toe grinding to improve fatigue strength is limited to following details of Table A.4:

- butt welds of type A2, A3 and A5 if they are ground from both sides
- non-load-carrying attachments of type C1, C2, C5 and C6 if they are completed with a full penetration weld
- transverse stiffeners of type C7
- doubling plates of type C9 if the weld throat thickness acc. to GL Rules for Hull Structures (1-1-1), Section 19 was increased by 30 %
- cruciform and T-joints of type D1 with full penetration welds

The corrected FAT class that can be reached by toe grinding is limited for all types of welded connections of steel to \( f_w \times \Delta \sigma_R = 100 \text{ N/mm}^2 \) and of aluminium to \( f_w \times \Delta \sigma_R = 40 \text{ N/mm}^2 \).

For butt welds ground flush the corresponding reference value of the S-N curve (FAT class) has to be chosen, e.g. type A1, A10 or A12 in Table A.4.

For endings of stiffeners or brackets, e.g. type C2 in Table A.4, which have a full penetration weld and are completely ground flush to achieve a notch-free transition, the following factor applies:

\[ f_w = 1,4 \]

The assessment of a local post-weld treatment of the weld surface and the weld toe by other methods e.g. ultrasonic impact treatment has to be agreed on in each case.

3.2.5 Influence of importance of structural element (\( f_i \))

For keel structural elements, the \( f_i \) factor has to be taken as:

\[ f_i = 0,9 \]
3.2.6 Plate thickness effect

In order to account for the plate thickness effect, application of the reduction factor \( f_t \) is required by GL for butt welds oriented transversely to the direction of applied stress for plate thicknesses \( t > 25 \text{ mm} \).

\[
f_t = \left( \frac{25}{t} \right)^n
\]

\( n = 0,17 \) as welded

\( n = 0,10 \) toe-ground

For all other weld connections consideration of the thickness effect may be required subject to agreement with GL.

C. Fatigue Strength Analysis for Welded Joints Based on Local Stresses

1. Alternatively to the procedure described in the preceding paragraphs, the fatigue strength analysis for welded joints may be performed on the basis of local stresses. For common plate and shell structures in ships the assessment based on the so-called structural (or hot-spot) stress \( \sigma_s \) is normally sufficient. The structural stress is defined as the stress being extrapolated to the weld toe excluding the local stress concentration in the local vicinity of the weld, see Fig. A.4.

![Fig. A.4 Structural stress](image)

2. The structural stress can be determined by measurements or numerically e.g. by the finite element method using shell or volumetric models under the assumption of linear stress distribution over the plate thickness. Normally the stress is extrapolated linearly to the weld toe over two reference points which are located 0,5 and 1,5 \( \times \) plate thickness away from the weld toe. In some cases the structural stress can be calculated from the nominal stress \( \sigma_n \) and a structural stress concentration factor \( K_s \), which has been derived from parametric investigations using the methods mentioned. Parametric equations should be used with due consideration of their inherent limitations and accuracy.

3. For the fatigue strength analysis based on structural stress, the S-N curves shown in Fig. A.2 apply with the following reference values:

\[
\Delta \sigma_R = 100 \text{ (resp. 40 for Al):}
\]

for the butt welds types A1 – A6 and for K-butt welds with fillet welded ends, e.g. type D1 in Table A.4, and for fillet welds which carry no load or only part of the load of the attached plate, type C1- C9 in Table A.4

\[
\Delta \sigma_R = 90 \text{ (resp. 36 for Al):}
\]

for fillet welds, which carry the total load of the attached plate, e.g. type D2 in Table A.4

In special cases, where e.g. the structural stresses are obtained by non-linear extrapolation to the weld toe and where they contain a high bending portion, increased reference values of up to 15 % can be allowed.

4. The reference value \( \Delta \sigma_{Rc} \) of the corrected S-N curve is to be determined according to B.3.2, taking into account the following additional correction factor which describes influencing parameters not included in the calculation model such as e.g. misalignment:

\[
f_s = \frac{1}{k_m - \frac{\Delta \sigma_{s,b}}{\Delta \sigma_{s,max}} \cdot (k_m^{-1})}
\]

\( \Delta \sigma_{s,max} = \) applied peak stress range within a stress range spectrum

\( \Delta \sigma_{s,b} = \) bending portion of \( \Delta \sigma_{s,max} \)

\( k_m = \) stress increase factor due to misalignments under axial loading, at least \( k_m \) acc. A.3.3

The permissible stress range or cumulative damage ratio, respectively, has to be determined according to B.2.

5. In addition to the assessment of the structural stress at the weld toe, the fatigue strength with regard to root failure has to be considered by analogous application of the respective FAT class, e.g. type D3 of Table A.4.

In this case the relevant stress is the stress in the weld cross section caused by the axial stress in the plate perpendicular to the weld. It is to be converted at a ratio of \( t/2a \).
## Table A.4 Catalogue of details

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Joint configuration showing mode of fatigue cracking and stress ( \sigma ) considered</th>
<th>Description of joint</th>
<th>FAT class ( \Delta \sigma_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steel</td>
<td>Al</td>
</tr>
<tr>
<td>A1</td>
<td>![Joint diagram]</td>
<td>Transverse butt weld ground flush to plate, 100 % NDT (Non-Destructive Testing)</td>
<td>112</td>
</tr>
<tr>
<td>A2</td>
<td>![Joint diagram]</td>
<td>Transverse butt weld made in shop in flat position, max. weld reinforcement 1 mm + 0.1 × weld width, smooth transitions, NDT</td>
<td>90</td>
</tr>
<tr>
<td>A3</td>
<td>![Joint diagram]</td>
<td>Transverse butt weld not satisfying conditions for joint type No. A2, NDT</td>
<td>80</td>
</tr>
<tr>
<td>A4</td>
<td>![Joint diagram]</td>
<td>Transverse butt weld on backing strip or three-plate connection with unloaded branch</td>
<td>71</td>
</tr>
<tr>
<td>A5</td>
<td>![Joint diagram]</td>
<td>Butt weld, welded on ceramic backing, root crack</td>
<td>80</td>
</tr>
<tr>
<td>A6</td>
<td>![Joint diagram]</td>
<td>Transverse butt welds between plates of different widths or thickness, NDT</td>
<td>71</td>
</tr>
<tr>
<td>A7</td>
<td>![Joint diagram]</td>
<td>Partial penetration butt weld; the stress is to be related to the weld throat sectional area, weld overfill not to be taken into account</td>
<td>36</td>
</tr>
<tr>
<td>Type No.</td>
<td>Joint configuration showing mode of fatigue cracking and stress σ considered</td>
<td>Description of joint</td>
<td>FAT class ΔσR</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------</td>
<td>---------------------</td>
<td>--------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Description of joint</td>
<td>Steel</td>
</tr>
<tr>
<td>A8</td>
<td></td>
<td>Full penetration butt weld at crossing flanges Welded from both sides.</td>
<td>50</td>
</tr>
<tr>
<td>A9</td>
<td></td>
<td>Full penetration butt weld at crossing flanges Welded from both sides Cutting edges in the quality according to type E2 or E3 Connection length w ≥ 2b $\sigma_{\text{nominal}} = \frac{F}{b \cdot t}$</td>
<td>63</td>
</tr>
<tr>
<td>A10</td>
<td></td>
<td>Full penetration butt weld at crossing flanges Welded from both sides, NDT, weld ends ground, butt weld ground flush to surface Cutting edges in the quality according to type E2 or E3 with $\Delta\sigma_R = 125$ Connection length w ≥ 2b $\sigma_{\text{nominal}} = \frac{F}{b \cdot t}$</td>
<td>80</td>
</tr>
<tr>
<td>A11</td>
<td></td>
<td>Full penetration butt weld at crossing flanges welded from both sides made in shop at flat position, radius transition with R ≥ b Weld reinforcement ≤ 1 mm + 0,1 x weld width, smooth transitions, NDT, weld ends ground Cutting edges in the quality according to type E2 or E3 with $\Delta\sigma_R = 125$</td>
<td>90</td>
</tr>
<tr>
<td>A12</td>
<td></td>
<td>Full penetration butt weld at crossing flanges, radius transition with R ≥ b Welded from both sides, no misalignment, 100 % NDT, weld ends ground, butt weld ground flush to surface Cutting edges broken or rounded according to type E2</td>
<td>100</td>
</tr>
</tbody>
</table>
Table A.4 Catalogue of details  (continued)

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Joint configuration showing mode of fatigue cracking and stress σ considered</th>
<th>Description of joint</th>
<th>FAT class ΔσR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steel</td>
</tr>
<tr>
<td>B1</td>
<td><img src="image1" alt="Joint B1" /></td>
<td>Longitudinal butt welds  both sides ground flush parallel to load direction  without start/stop positions, NDT  with start/stop positions</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>B2</td>
<td><img src="image2" alt="Joint B2" /></td>
<td>Continuous automatic longitudinally fully penetrated K-butt butt weld without stop/start positions (based on stress range in flange adjacent to weld)</td>
<td>125</td>
</tr>
<tr>
<td>B3</td>
<td><img src="image3" alt="Joint B3" /></td>
<td>Continuous automatic longitudinal fillet weld penetrated K-butt weld without stop/start positions (based on stress range in flange adjacent to weld)</td>
<td>100</td>
</tr>
<tr>
<td>B4</td>
<td><img src="image4" alt="Joint B4" /></td>
<td>Continuous manual longitudinal fillet or butt weld (based on stress range in flange adjacent to weld)</td>
<td>90</td>
</tr>
<tr>
<td>B5</td>
<td><img src="image5" alt="Joint B5" /></td>
<td>Intermittent longitudinal fillet weld (based on stress range in flange at weld ends)  In presence of shear τ in the web, the FAT class has to be reduced by the factor ((1 – \Delta\sigma / \Delta\sigma)), but not below 36 (steel) or 14 (Al).</td>
<td>80</td>
</tr>
<tr>
<td>B6</td>
<td><img src="image6" alt="Joint B6" /></td>
<td>Longitudinal butt weld, fillet weld or intermittent fillet weld with cut outs (based on stress range in flange at weld ends)  If cut out is higher than 40 % of web height  In presence of shear τ in the web, the FAT class has to be reduced by the factor ((1 – \Delta\tau / \Delta\sigma)), but not below 36 (steel) or 14 (Al).</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Note</strong>  For Ω-shaped scallops, an assessment based on local stresses in recommended.</td>
<td>63</td>
</tr>
</tbody>
</table>
### Table A.4 Catalogue of details (continued)

#### C. Non-load-carrying attachments

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Joint configuration showing mode of fatigue cracking and stress $\sigma$ considered</th>
<th>Description of joint</th>
<th>FAT class $\Delta\sigma_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C1</strong></td>
<td>Longitudinal gusset welded on beam flange, bulb or plate:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\ell \leq 50$ mm</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>$50$ mm $&lt; \ell \leq 150$ mm</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>$150$ mm $&lt; \ell \leq 300$ mm</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>$\ell &gt; 300$ mm</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>For $t_2 \leq 0.5$ $t_1$, $\Delta\sigma_R$ may be increased by one class, but</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>not over 80 (steel) or 28 (Al); not valid for bulb profiles.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>When welding close to edges of plates or profiles (distance less than 10 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and/or the structural element is subjected to bending, $\Delta\sigma_R$ is to be</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>decreased by one class.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>C2</strong></td>
<td>Gusset with smooth transition (sniped end or radius)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>welded on beam flange, bulb or plate;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c \leq 2$ $t_2$, max. 25 mm</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>$r \geq 0.5$ h</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>$r &lt; 0.5$ h and $\varphi \leq 20^\circ$</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>$\varphi &gt; 20^\circ$ see joint type C1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>For $t_2 \leq 0.5$ $t_1$, $\Delta\sigma_R$ may be increased by one class;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>not valid for bulb profiles.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>When welding close to the edges of plates or profiles (distance less than 10 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and/or the structural element is subjected to bending, $\Delta\sigma_R$ is to be</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>decreased by one class.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>C3</strong></td>
<td>Fillet welded non-load-carrying lap joint welded to longitudinally stressed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>component.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– flat bar</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>– to bulb section</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>– to angle section</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>For $\ell &gt; 150$ mm, $\Delta\sigma_R$ has to be decreased by one class, while</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>for $\ell \leq 50$ mm, $\Delta\sigma_R$ may be increased by one class.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>If the component is subjected to bending, $\Delta\sigma_R$ has to be reduced by</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>one class.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>C4</strong></td>
<td>Fillet welded lap joint with smooth transition (sniped end with $\varphi \leq 20^\circ$ or radius)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>welded to longitudinally stressed component.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– flat bar</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>– to bulb section</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>– to angle section</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>$c \leq 2$ $t_2$, max. 25 mm</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td><strong>C5</strong></td>
<td>Longitudinal flat side gusset welded on plate or beam flange edge</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\ell \leq 50$ mm</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>$50$ mm $&lt; \ell \leq 150$ mm</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>$150$ mm $&lt; \ell \leq 300$ mm</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>$\ell &gt; 300$ mm</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>For $t_2 \leq 0.7$ $t_1$, $\Delta\sigma_R$ may be increased by one class, but</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>not over 56 (steel) or 20 (Al).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>If the plate or beam flange is subjected to in-plane bending, $\Delta\sigma_R$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>has to be decreased by one class.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### C. Non-load-carrying attachments

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Joint configuration showing mode of fatigue cracking and stress σ considered</th>
<th>Description of joint</th>
<th>FAT class ΔσR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steel</td>
<td>Al</td>
</tr>
<tr>
<td>C6</td>
<td>Longitudinal flat side gusset welded on plate edge or beam flange edge, with smooth transition (snipped end or radius); ε ≤ 2 t2, max. 25 mm</td>
<td>50</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>r ≥ 0,5 h</td>
<td>45</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>r &lt; 0,5 h or ϕ ≤ 20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ϕ &gt; 20° see joint type C5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>For t2 ≤ 0,7 t1, ΔσR may be increased by one class.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6a</td>
<td>Longitudinal flat side gusset welded on plate edge or beam flange edge, with smooth transition radius r/h &gt; 1/3 or r ≥ 150 mm</td>
<td>90</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>1/6 &lt; r/h &lt; 1/3</td>
<td>71</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>r/h &lt; 1/6</td>
<td>50</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Smooth transition radius formed by grinding the full penetration weld area in order to achieve a notch-free transition area. Final grinding shall be performed parallel to stress direction.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Transverse stiffener with fillet welds (applicable for short and long stiffeners)</td>
<td>80</td>
<td>28</td>
</tr>
<tr>
<td>C8</td>
<td>Non-load-carrying shear connector</td>
<td>80</td>
<td>28</td>
</tr>
<tr>
<td>C9</td>
<td>End of long doubling plate on beam, welded ends (based on stress range in flange at weld toe)</td>
<td>56</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>tD ≤ 0,8 t</td>
<td>50</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>0,8 t &lt; tD ≤ 1,5 t</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tD &gt; 1,5 t</td>
<td>45</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>The following features increase ΔσR by one class accordingly:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– reinforced ends according to Section 19, Fig. 19.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– weld toe angle ≤ 30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– length of doubling ≤ 300 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>For length of doubling ≤ 150 mm, ΔσR may be increased by two classes.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Table A.4 Catalogue of details (continued)

## D. Cruciform joints and T-joints

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Joint configuration showing mode of fatigue cracking and stress $\sigma$ considered</th>
<th>Description of joint</th>
<th>FAT class $\Delta\sigma_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td><img src="image1" alt="Cruciform joint" /></td>
<td>Cruciform or tee-joint K-butt welds with full penetration or with defined incomplete root penetration according to Section 19, Fig. 19.9.</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cruciform joint</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tee-joint</td>
<td>80</td>
</tr>
<tr>
<td>D2</td>
<td><img src="image2" alt="Cruciform joint" /></td>
<td>Cruciform or tee-joint with transverse fillet welds, toe failure (root failure particularly for throat thickness $a &lt; 0.7 \cdot t$, see joint type D3)</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cruciform joint</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tee-joint</td>
<td>71</td>
</tr>
<tr>
<td>D3</td>
<td><img src="image3" alt="Cruciform joint" /></td>
<td>Welded metal in transverse load-carrying fillet welds at cruciform or tee-joint, root failure (based on stress range in weld throat), see also joint type No. D2</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$a \geq t/3$</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$a &lt; t/3$</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td><img src="image4" alt="Note" /></td>
<td>Crack initiation at weld root</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td><img src="image5" alt="Cruciform joint" /></td>
<td>Full penetration weld at the connection between a hollow section (e.g. pillar) and a plate, for tubular section and for rectangular hollow section</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t \leq 8$ mm</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t &gt; 8$ mm</td>
<td>50</td>
</tr>
<tr>
<td>D5</td>
<td><img src="image6" alt="Cruciform joint" /></td>
<td>Fillet weld at the connection between a hollow section (e.g. pillar) and a plate, for tubular section and for rectangular hollow section</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t \leq 8$ mm</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t &gt; 8$ mm</td>
<td>40</td>
</tr>
<tr>
<td>D6</td>
<td><img src="image7" alt="Cruciform joint" /></td>
<td>Continuous butt or fillet weld connecting a pipe penetrating through a plate</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d \leq 50$ mm</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d &gt; 50$ mm</td>
<td>63</td>
</tr>
</tbody>
</table>

**Note**

For large diameters an assessment based on local stress is recommended.
### Table A.4 Catalogue of details (continued)

#### E. Unwelded base material

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Joint configuration showing mode of fatigue cracking and stress σ considered</th>
<th>Description of joint</th>
<th>FAT class ΔσR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Steel</strong></td>
</tr>
<tr>
<td>E1</td>
<td><img src="image" alt="Illustration" /> Rolled or extruded plates and sections as well as seamless pipes, no surface or rolling defects</td>
<td></td>
<td>160 (m₀ = 5)</td>
</tr>
<tr>
<td>E2a</td>
<td><img src="image" alt="Illustration" /> Plate edge sheared or machine-cut by any thermal process with surface free of cracks and notches, cutting edges chamfered or rounded by means of smooth grinding, groove direction parallel to the loading direction. Stress increase due to geometry of cut-outs to be considered by means of direct numerical calculation of the appertaining maximum notch stress range.</td>
<td></td>
<td>150 (m₀ = 4)</td>
</tr>
<tr>
<td>E2</td>
<td><img src="image" alt="Illustration" /> Plate edge sheared or machine-cut by any thermal process with surface free of cracks and notches, cutting edges broken or rounded. Stress increase due to geometry of cut-outs to be considered.¹</td>
<td></td>
<td>140 (m₀ = 4)</td>
</tr>
<tr>
<td>E3</td>
<td><img src="image" alt="Illustration" /> Plate edge not meeting the requirements of type E2, but free from cracks and severe notches. Machine cut or sheared edge: Manually thermally cut: Stress increase due to geometry of cut-outs to be considered.¹</td>
<td></td>
<td>125 (m₀ = 3,5)</td>
</tr>
</tbody>
</table>

¹ Stress concentrations caused by an opening to be considered as follows:

\[ Δσ_{\text{max}} = K_t \cdot Δσ_N \]

- **Kₜ**: Notch factor according to Section 3, J.
- **Δσₑ**: Nominal stress range related to net section

Alternatively, direct determination of \( Δσ_{\text{max}} \) from FE-calculation, especially in case of hatch openings or multiple arrangement of openings.

Partly based on Recommendations on Fatigue of Welded Components, reproduced from IIW document XIII-2151-07 / XV-1254-07, by kind permission of the International Institute of Welding.
### Table A.5 Various intersection

<table>
<thead>
<tr>
<th>Joint configuration</th>
<th>Description of joint</th>
<th>FAT class $\Delta \sigma_R$ steel</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Joint configuration" /></td>
<td>None watertight intersection without heel stiffener. For predominant longitudinal load only.</td>
<td>80 80 80 80</td>
</tr>
<tr>
<td><img src="image" alt="Joint configuration" /></td>
<td>Watertight intersection without heel stiffener (without cyclic load on the transverse member, see Section 9, B.4.1) For predominant longitudinal load only</td>
<td>71 71 71 71</td>
</tr>
<tr>
<td><img src="image" alt="Joint configuration" /></td>
<td>With heel stiffener direct $l \leq 150$ connection $l &gt; 150$ overlapping $l \leq 150$ connection $l &gt; 150$</td>
<td>45 56 56 63 40 50 50 56 45 50 45 56</td>
</tr>
<tr>
<td><img src="image" alt="Joint configuration" /></td>
<td>With heel stiffener and integrated bracket</td>
<td>45 56 56 63</td>
</tr>
<tr>
<td><img src="image" alt="Joint configuration" /></td>
<td>With heel stiffener and integrated bracket and with backing bracket direct connection overlapping connection</td>
<td>50 56 63 63 56 50 71</td>
</tr>
<tr>
<td><img src="image" alt="Joint configuration" /></td>
<td>With heel stiffener but considering the load transferred to the stiffener (see Section 9, B.4.9) crack initiation at weld toe crack initiation at weld root Stress increase due to eccentricity and shape of cut out has to be observed</td>
<td>80 71 40 40 71 40 40</td>
</tr>
</tbody>
</table>

1 Additional stresses due to asymmetric sections have to be observed, see Section 3.4.

2 To be increased by one class, when longitudinal loads only.
### Table A.6 Examples of details

<table>
<thead>
<tr>
<th>EAF class</th>
<th>Description of Joint</th>
<th>Type No.</th>
<th>71</th>
<th>63</th>
<th>36</th>
<th>71</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R_{N}$</td>
<td>Cruciform or tee-joint K-butt welds with full penetration or with defined incomplete root penetration according to Section 19, cruciform joint</td>
<td>D1</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R_{N}$</td>
<td>Cruciform or tee-joint with transverse fillet welds, see failure (root failure particularly in case of double welds, see Section 19, cruciform joint)</td>
<td>D2</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R_{N}$</td>
<td>Welded joint in transverse load carrying fillet welds at cruciform or tee-joint (based on stress range in weld throat), see also joint type No. D2</td>
<td>D3</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R_{N}$</td>
<td>Welded joint in transverse load carrying fillet welds at cruciform or tee-joint (based on stress range in weld throat), see also joint type No. D2</td>
<td>C1</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Diagram:**
- **D1:** Joint configuration showing how the stress $\sigma$ is calculated.
- **D2:** Joint configuration showing how the stress $\sigma$ is calculated.
- **D3:** Joint configuration showing how the stress $\sigma$ is calculated.
- **C1:** Holder added in the way of an opening and arranged parallel to the edge of the joint.

**Equations:**
- For D1: $\sigma = F_{k} \frac{a_{i}}{b_{i}} 2 \sin \alpha$
- For D2: $\sigma = F_{k} \frac{a_{i}}{b_{i}} 2 \sin \alpha$
Table A.6  Examples of details  (continued)

<table>
<thead>
<tr>
<th>EAT class ΔfR</th>
<th>Description of joint</th>
<th>Joint configuration showing mode of fatigue loading and stress σs considered</th>
<th>Type No.</th>
<th>Description of structure or equipment detail</th>
<th>Structure or equipment detail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>71 63 56</td>
<td></td>
<td>C9</td>
<td>Circular doubler plate with max. 150 mm diameter.</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td>71 63 56</td>
<td></td>
<td>C9</td>
<td>Drain plugs with full penetration butt weld d ≤ 150 mm</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C9</td>
<td>Drain plugs with partial penetration butt weld and a defined root gap</td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial penetration butt weld; the stress is to be related to the weld throat sectional area, weld overlap not to be taken into account</td>
<td>A7</td>
<td>The detail category is also valid for fully circumferential welded holders</td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C7</td>
<td>For stiffeners loaded in bending ΔfR to be downgraded by one class</td>
<td><img src="image5" alt="Diagram" /></td>
</tr>
</tbody>
</table>

For d > 150 mm, ΔfR has to be decreased by one class.

For d < 0.8d, ΔfR = 0.81.

For 0.8d < d ≤ 1.5d, ΔfR has to be decreased by one class.

For 1.5d < d < 2.0d, ΔfR has to be decreased by one class.