RULES FOR CLASSIFICATION

Yachts

Edition January 2018
Amended July 2018

Part 3 Hull

Chapter 5 Composite scantlings

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FOREWORD

DNV GL rules for classification contain procedural and technical requirements related to obtaining and retaining a class certificate. The rules represent all requirements adopted by the Society as basis for classification.

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CURRENT – CHANGES

This document supersedes the January 2018 edition of DNVGL-RU-YACHT Pt.3 Ch.5.

Changes in this document are highlighted in red colour. However, if the changes involve a whole chapter, section or subsection, normally only the title will be in red colour.

Amendments July 2018

- Only editorial corrections have been made.

Changes January 2018, entering into force 1 July 2018

Topic	*Reference*	*Description*
Small modifications	Sec.6 Table 9	Minor relaxation of acceptable deflection requirements (aligning rule change with DNVGL-RU-HSLC)

Editorial corrections

In addition to the above stated changes, editorial corrections may have been made.

CONTENTS

SECTION 1 INTRODUCTION

1 General

1.1 Application

1.1.1 This rule chapter applies to yachts being constructed from fibre reinforced thermoset matrix composites (FRP), typically in single skin and/or sandwich construction using glass, carbon or aramid fibres.

Alternative material combinations may be accepted after special consideration.

1.1.2 This rule chapter envisages primarily structural integrity of vessels hull including structural components listed in Ch.1 Sec.1.

Guidance note:

Any note in this chapter addressing issues other than relating to structural integrity shall be considered as recommendation or guidance to designer, builder, owner, et al.

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1.1.3 A single skin construction is considered to be a structure consisting of an FRP laminate supported and stiffened locally by a system of relatively closely spaced FRP stiffeners.

1.1.4 A sandwich construction is considered to be a structural element consisting of three components: a FRP skin laminate on each side of a lower density core.

1.1.5 The methodologies offered in this chapter are especially suitable for vessel structures composed by and designed to a clear hierarchy of structural elements, i.e.:

— plating
— stiffeners
— girders
— bulkheads
— hull.

Any other types of structural arrangements require individual case-by-case evaluation by the Society.

1.1.6 Neither all facets nor all elements of structural design can be covered by this chapter. For structural elements not completely covered by this chapter alternative methods may be applied subject to the acceptance by the Society.

1.1.7 Construction shall be carried out according to DNVGL-RU-SHIP Pt.2 Ch.4 *Fabrication and testing*.

1.2 Rules compliance equivalence

1.2.1 Designs deviating from the requirements or the methodologies of this chapter in their type or design may be approved, provided that their structures are recognized by the Society to be equivalent to the Society's requirements. The term equivalent shall be understood as to:

— providing the same level of structural reliability, if not higher; for all relevant load cases specified in the rules
— resulting in at least the same expected operational life time.

2 Documentation

2.1 Documentation

The documentation required by Table 1 shall be submitted.

a) Details of all laminates and panels: the mechanical properties used for the design, see Sec.2 [2.1] and fabrication method (e.g. manual lamination or VARTM etc.).

b) Plan for qualification testing and as-built testing, Sec.3.

Table 1 Documentation requirements

Object	*Documentation type*	*Additional description*	*Info*
Structural materials, composite	M030 – Material specification, non metallic materials	Specifications of all: — reinforcement fabrics — all resins — core materials and adhesives.	AP
	Z110 – Data sheet	For each laminate and panel: — identification — stacking sequence including references to specifications of reinforcement and resins — engineering moduli as relevant. For orthotropic laminates the engineering moduli in the two principal directions and the shear modulus shall be given — tensile strength and compressive strength or strain — shear strength — fibre volume fraction — laminate thickness — fabrication method (e.g. manual lamination or VARTM).	AP
	Z120 – Test procedure at manufacturer	Qualification testing.	AP

For general requirements for documentation, including definition of the info codes, see DNVGL-RU-SHIP Pt.1 Ch.3 Sec.2.

For a full definition of the documentation types, see DNVGL-RU-SHIP Pt.1 Ch.3 Sec.3.

Plan approval will normally not be initiated until all of the documents have been submitted.

The laminate details shall be presented in the form of a table or on an equivalent format.

2.2 Certification requirements

2.2.1 For products that shall be installed on board, the builder shall request the manufacturers to order certification as described in Table 2.

Table 2 Certification requirements

Object	*Certificate type*	*Issued by*	*Certification standard**	*Additional description*
Structural materials, composite	TA	The Society		Reinforcement, matrix, core materials, adhesives and core adhesives
	MC	Manufacturer		
* Unless otherwise specified the certification standard is the rules.				

For general certification requirements, see DNVGL-RU-SHIP Pt.1 Ch.3 Sec.4.

For a definition of the certification types, see DNVGL-RU-SHIP Pt.1 Ch.1 Sec.4 and DNVGL-RU-SHIP Pt.1 Ch.3 Sec.5.

SECTION 2 MATERIALS

1 General

In this section requirements regarding the application of structural materials as well as material protection and material testing are given.

1.1 Laminating resins for hull, superstructure and deckhouses

The laminating resin (matrix) in hull and superstructure may be polyester, vinylester or epoxy. Other types may be accepted based on special consideration.

When using polyester, Grade 1 polyester shall be used for the hull shell laminate in single skin constructions and for the outer hull skin laminate in sandwich construction. For the inner skin laminate and superstructure grade 2 polyester may be accepted. Specifications for grade 1 and grade 2 polyester resins are given in DNVGL-RU-SHIP Pt.2 Ch.3 Sec.2 Table 11.

1.2 Surface coating

The underwater part of the hull, the inside of tanks for liquids and other areas exposed to permanent liquid submergence shall have an efficient surface coating or lining, such as gelcoat, topcoat, an epoxy based painting or polyurethane of sufficient thickness. The surface lining of tanks is as far as practicable to be laid continuously in the tanks side and bottom.

Weather exposed surfaces shall have a suitable surface coating.

For inspection purposes the surface coating internally in the hull bottom and in tanks is wherever feasible to be unpigmented.

Where pigments are used, light colours should be used to expose damage and cracks more readily.

1.3 Mechanical properties

1.3.1 The mechanical properties of laminates depend on the properties of the constituent materials, fibres and matrix. It is however recognised that the mechanical properties of the laminates (in terms of mean strength and variability) in the finished product to a significant degree also depend on the production process and the control of the same. Test data from purpose made test laminates may not be entirely representative for the finished product. This is reflected in the specified reserve factors Sec.6 [7.2].

1.3.2 Sufficient control of the mechanical properties of the finished product shall be ensured by adhering to the requirements to manufacturing and production facilities given in as specified in DNVGL-RU-SHIP Pt.2 Ch.3 Sec.3 *Manufacturing of products made of FRP* and by verification through qualification testing and/or as-built testing as defined in [3].

2 Constituent materials

2.1 Material properties for structural design

2.1.1 The mechanical strength and moduli of laminates can either be determined by testing as prescribed in [3] or default values can be used as prescribed in Sec.6 [7]. When using default values testing is not required.

The shear strength and modulus of core materials shall be specified and verified by testing in accordance with the Society’s requirements for type approval for such materials. For core materials already type approved testing of the core material itself is not required, but the (msmv; manufacturer minimum specified value) values stated on the type approval certificate shall be used in design. Core materials for use in slamming exposed areas shall be type approved for such service or such testing shall be carried out with acceptable results according to the Society's requirements for such service.

Core materials, core adhesives can be considered finished products when received by the yard, as opposed to laminates.

The mechanical properties of the core material of structural sandwich panels shall comply with the minimum requirements given in Table 1.

Table 1 Minimum core mechanical strength

Structural member	*Core strength (MPa)*	
	Shear strength	*Compression strength*
Hull bottom, side and transom below deepest WL or chine whichever is higher	0.8	0.9
Hull side and transom above deepest WL or chine whichever is higher	0.8	0.9
Weather deck not intended for cargo	0.5	0.6
Cargo deck	0.8	0.9
Accommodation deck	0.5	0.6
Structural/watertight bulkheads/double bottom	0.5	0.6
Superstructures and deck-houses	0.5	0.6
Tank bulkheads	0.5	0.6

3 Mechanical testing

3.1 Qualification testing

Qualification testing is the procedure to derive material properties for structural design purposes, based on material tests. Qualification testing is required for the case that individual mechanical material properties are intended to be used for the purpose of structural design. The procedure is described in the following.

The purpose of the testing is to generate data for the resins, fibres and cores (and the relevant combinations thereof) to be used in production as well as to confirm the yards adequate skills in the manufacturing of laminates.

3.1.1 Qualification testing is not required for the case that default mechanical properties are used, as further specified in Sec.6 [7.2.3]. In this case the present [3.1] does not need to be considered.

3.1.2 For material combinations or lay-ups for which insufficient data with respect to fatigue, environmental effects, etc. has been documented additional testing may be required.

If considered necessary, the strength of the bonds between structural members or other structural details may be subject to relevant qualification testing.

The mechanical properties shall be based on mechanical tests carried out on samples that are representative for the raw materials, production method(s), workshop conditions, lay-up sequence etc. that are used as well as on specimens suitable for testing purposes. This mechanical testing comes in addition to the testing required for type approval of fibres, resins adhesives etc.

For well-known reinforcements and resin combinations and production methods the mechanical properties of laminates may be based on standard engineering analytical methods, such as micro mechanics, laminate theory etc., substantiated by a reduced amount of testing.

3.1.3 The testing is the responsibility of the yard and shall normally be approved by the Society prior to carrying out the design of the vessel. The yard shall submit a plan for testing for approval by the Society prior to hull plans being approved. The plan for testing may invoke results from previous representative and well documented testing. The test methods specified in [4] shall be used. The yard may use subcontractor(s) for testing.

3.1.4 The testing shall represent lay-ups of different types of structural components and the relevant mechanical properties. The test plan shall address the items given in Table 2, but is the subject of individual consideration and approval of the Society.

The testing is normally to be carried out at room temperature. If relevant to the operation of the vessel the testing may be required to be carried out at other representative operating temperatures.

Table 2 Items to test

Item	*Property*
Single and sandwich skin laminates	Tensile strength
	Compressive strength
	Shear strength 1)
Flanges of girders, web frames, stiffeners	Tensile strength
	Compressive strength
Webs of girders, web frames, stiffeners	Shear strength 1)
Bond between core and skin in sandwich panels	Shear strength
1) In plane shear strength may be derived from uniaxial test in tension and compression in the fibre direction by the use of laminate theory as an alternative to testing.	

3.2 As-built testing

3.2.1 As-built testing is required to verify that the assumptions regarding the reference mechanical strength used during design are adequate and that a consistent level of quality is maintained throughout production.

3.2.2 As-built testing shall be carried out independent from whether qualification tests were carried out or not.

3.2.3 The yard shall specify an as-built test plan, as part of the quality plan, which as a minimum shall address the following items:

- mechanical strength of sandwich skin laminates, single skin laminates, flanges (caps) of stringers and girders
- bond strength between core and skin laminates in sandwich panels
- mechanical strength of major attachments and joints
- acceptance criteria.

The extent of testing is not to be smaller than provided in Table 3.

Table 3 Extent of testing

Area	*Testing*
Hull bottom, sandwich	Tensile tests of outer skin
Hull bottom, single skin	Tensile tests of bottom panel
Main deck, sandwich	Tensile tests of outer skin
Main deck, single skin	Tensile tests of panel
1 off main girder or stringer	Tensile tests of top flange/cap
Hull bottom, sandwich	Flexural test or through thickness tests

3.2.4 The test methods specified in [4] shall be used. For details considered critical with respect to compressive loads compression tests may be required instead of or in addition to the tensile tests.

3.2.5 The test samples shall be taken from cut-outs in the hull and main deck. All such cut-outs shall be identified by marking and stored until used for testing purposes or until completion of the vessel. If adequate cut-outs are not possible to obtain, alternative methods to verify the mechanical strength of the structures shall be agreed upon with the Society.

3.2.6 Material selection, design, fabrication methods and QA/QC procedures may differ significantly between different vessels and yards. A larger or different extent of testing may therefore be required by the Society. The extent of testing may also be made dependent on the degree of the structural importance and the level of utilisation of the particular component or the consequences of a failure of the component.

3.2.7 The test results shall be submitted to and reviewed by the responsible hull plan approval engineer. The test results shall be in accordance with the values of reference mechanical strength used in the design and indicate a level of workmanship in line with DNVGL-RU-SHIP Pt.2 Ch.4. Deviations on the negative side of the test results from the mechanical strength used in the design will render the approval of the design invalid. In such case a renewed approval of the affected areas shall be carried out, or reinforcements may be necessary.

4 Testing procedures

4.1 Test standards

4.1.1 Mechanical properties shall be tested according to the following test standards or their alternatives as listed in Table 4 below.

Tests are preferably to be performed using ISO standards, other standards may be acceptable as listed or as per special agreement.

Table 4 Test standards

Property	*Test method*	*Comment*
Tensile strength/modulus for multiaxial laminates	ISO 527-4 specimen type 3	For multiaxial fabrics
	(ASTM D638-10 for dogbone specimen)	For reinforced laminates
Tensile strength/modulus for UD laminates	ISO 527-5 specimen type A	For tests parallel to the fibre
	ISO 527-5 specimen type B	For tests perpendicular to the fibre
	(ASTM D3039 straight specimen)	For laminates with continuous fibres
Compressive strength/modulus for laminates	ISO 14126 specimen type B1; method 1	Loading the specimen by shear
	ASTM D3410 with Celanese test fixture	For laminates with continuous fibres
In-Plane shear strength/modulus for laminates	ISO 14129	Most commonly used method
	(ASTM D4255)	For all laminates
Shear strength/modulus for core materials	ISO 1922	
	ASTM C273	Tension test version to be used
Interlaminar shear strength	ISO 14130	For single skin laminates
	(ASTM D2344)	For single skin laminates
Sandwich flexural properties	ASTM D7249	
Sandwich through-thickness shear properties	ASTM C393	Beam length adjusted for promoted core shear failure
Laminate flexural strength and stiffness	ISO 178 or ISO 14125	

4.2 Test results

4.2.1 A minimum of five parallel valid test results shall be obtained for each test series representing one type of test on one test laminate/panel. The reference mechanical strength F_r shall be calculated from the test results as:

$$F_r = \mu - 2.4 \cdot \sigma$$

where:

μ = value of the test results

σ = standard deviation of the test results

$= \sqrt{\frac{1}{n-1}\sum_{i}^{n}\left(X_i - \mu\right)^2}$

n = number of tests, ≥ 5

x_i = test results.

The elastic modulus, when used as prescribed in these rules, shall be calculated as the mean value of the measured modulus on relevant test specimens.

4.2.2 Strength of laminates consisting of unidirectional plies only

The strength of laminates built up from a number of types of plies, e.g. unidirectionals (UD) only or UD's combined with woven rowing (WR) can be found by the application of tests results obtained for each ply type only and combined by the use of standard laminate theory and micromechanics for each laminate stack. The capacity of the laminate will be determined by the ply with smallest strain capacity in the load direction.

4.2.3 Compressive strength

Compression testing of plies/laminates may not be required if the compression strength used in design does not exceed a given percentage of the tensile strength of the same ply/laminate. The following requirements shall be complied with in that case:

Glass reinforcement	:	Design compressive strength ≤ 75% of design tensile strength
Carbon reinforcement	:	Design compressive strength ≤ 60% of design tensile strength for HS carbon [1)]
Aramid reinforcement	:	Design compressive strength ≤ 45% of design tensile strength

1) Compressive strength of HM carbon shall be determined by testing.

SECTION 3 STRUCTURAL ARRANGEMENTS

1 General

1.1 Hierarchy of structures

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

1.1.2 Where bulkheads, bunks, shelves, or other structurally effective interior components are laminated to the hull to provide structural support, they shall be adequately bonded.

1.2 Structural continuity

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

1.3 Access

1.3.1 Access for visual routine inspection of structures shall be possible for all essential structural elements related to global strength, water and weathertight integrity, keel attachment, chain plates and rudder support structures.

In case of a damage inspection it can be acceptable that access will be possible only after more intrusive operation.

Compartements without possible access through hatches or similar are not acceptable, except when completely filled with buoyancy foam.

1.4 Bulkheads

1.4.1 The number and location of transverse watertight bulkheads shall be in accordance with the requirements for the ship type notation in question.

1.4.2 Bulkheads shall be arranged and designed to cope with global and local strength requirements. They shall carry, transfer and distribute lateral design loads on hull and deck, pick up reaction forces from girders and carry sufficient stress compensation relief around cut-outs.

1.5 Superstructure and deckhouses

1.5.1 In superstructures and deckhouses, the front bulkhead shall be in line with a transverse bulkhead in the hull below or be supported by a combination of girders and pillars. The after end bulkhead is also to be effectively supported. As far as practicable, exposed sides and internal longitudinal and transverse bulkheads shall be located above girders and frames in the hull structure and shall be in line in the various tiers of accommodation. Where such structural arrangement in line is not possible, there shall be other effective support.

1.5.2 Sufficient transverse strength shall be provided by means of transverse bulkheads or girder and web frame structures.

1.5.3 At the break of superstructures, which have not set-in from the ship's side, the side plating shall extend beyond the ends of the superstructure, and shall be gradually reduced in height down to the deck or bulwark. The transition shall be smooth and without local discontinuities.

1.5.4 In long deckhouses, openings in the sides shall have well rounded corners. The perimeter of any opening (with a hatch, door or window) shall be able to support the specified load corresponding to the area of the opening and adjoining panels.

SECTION 4 PRINCIPLES OF STRUCTURAL DESIGN AND CALCULATION

1 General

1.1 Composites

FRP exhibits close to linear behaviour to failure as long as the response is fibre dominated and shows little or no yielding behaviour before failure. Consequently, special attention is needed in structural design, e.g. in connection with stress concentrations.

Through thickness strength is smaller by orders of magnitude than in plane strength. Although it is a requirement that loads shall coincide to a large degree with fibre directions, through thickness stress cannot always be avoided completely and shall be handled in a conservative way. Delamination caused by overloading, impact or deficient design is an important cause of subsequent failure and contributor to fatigue failure.

Not all parts are suitable for FRP. Complex 3-dimensional stress states may make the use of other materials necessary.

1.2 Principles of laminate lay-up

1.2.1 The design of the vessel shall be based on mechanical properties that are representative for the raw materials, production method(s), workshop conditions, lay-up sequence etc. that are used.

1.2.2 The vessel shall be designed such that the load(s) are carried mainly by the fibres. The fibres shall be aligned close to the direction(s) of the main load path(s).

1.2.3 Preferably laminates shall be homogeneous, symmetrical and balanced. If not, due attention shall be given to possible secondary effects.

1.2.4 The failure mechanism of a laminate shall be fibre failure. Matrix failure shall be controlled by having fibres in a sufficient number of directions and by a stacking sequence avoiding fibre clusters. Groups of plies with the same fibre direction shall not exceed 1.5 mm in thickness.

Deviations may be accepted in local areas of details that are well proven and for minor loads of secondary nature.

1.2.5 Significant through thickness tensile load in laminates and sandwich panels shall be avoided as far as possible. Although no specific scantling requirements are given in these rules the Society may require modifications to designs where the combination of the magnitude of the through thickness loads and the consequence of a failure is considered unacceptable by the Society.

Laminates exposed to through thickness compressive loads shall be designed with the same reserve factor as specified elsewhere for laminates in these rules.

1.2.6 Unlike metallic constructions, joints between different structural FRP elements may present challenges when ensuring structural continuity, e.g. through bulkheads. Special consideration to the continuity of plies of load carrying fibres shall be given.

1.3 Minimum areal weight of reinforcement

1.3.1 Minimum requirements to the weight of reinforcement in single skin and sandwich laminates are given in Sec.7 [2]. These minimum requirements apply also if scantling requirements indicate the need for a lower weight.

The intention of these minimum requirements shall provide a reasonable resistance to wear, tear and local impact. Deviations from these minimum requirements may be accepted for exposed surfaces if such resistance is provided by other means. Such deviations are the subject of agreement by the Society.

2 Failure criteria

2.1 Failure criteria - laminates

2.1.1 The default failure criterion for laminates is maximum strain in the fibre direction. Load effects and allowables are expressed as strain in the fibre direction. This is based on the requirements given in [1.1] being fulfilled.

Ultimate stress may alternatively be used as failure criterion in accordance with [2.5].

2.1.2 Other recognized laminate failure criteria may be used, e.g. Tsai-Wu or Puck. The use of such criteria requires more material data than fibre strain to failure. Such data shall be determined by material testing according to the principle prescribed in Sec.2 [3], Sec.2 [4] shall be applied; alternatively conservative assumptions shall be used.

An acceptable modification of the Tsai-Wu criterion for verifying fibre maximum strain criterion is given in DNVGL-OS-C501.

The use of other failure criteria is subject to approval by the Society.

2.1.3 The maximum strain to failure ε_{uf} is defined by the following equation and as shown in Figure 1.

$$\varepsilon_{uf} = \frac{\sigma_u}{E_r}$$

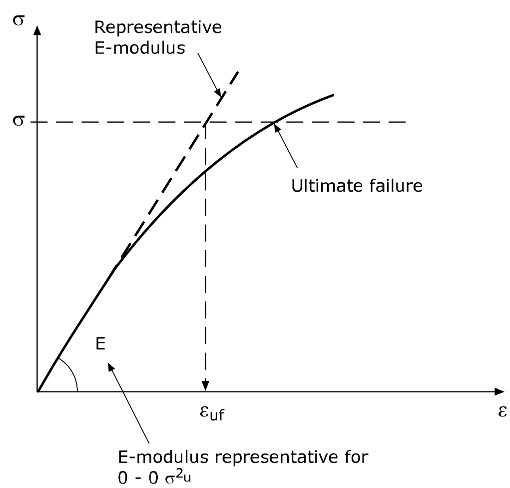

Figure 1 Stress strain relation

σ_u	=	ultimate tensile or compressive strength
E_r	=	representative E modulus for the laminate in the range of allowable stresses (see Sec.6). The representative modulus is defined as secant modulus at 0.3 σ_u determined either by measurements or by laminate theory.

Guidance note:

In most cases the E modulus as defined in ISO 527-4 and ISO 527-5 will qualify as representative E modulus.

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2.1.4 The reference mechanical strength F_r in terms of strain to failure can either be determined by testing as prescribed in Sec.2 [3] or by using default values prescribed in Sec.6 [7].

Mixing of default values and values determined by testing is subject to approval by the Society.

2.2 Failure criteria – core materials

The failure criteria for core materials are maximum core shear stress and compressive stress.

2.3 Failure criteria – bonds

The failure criterion for laminated bonds and adhesive bonds is bond-line shear stress.

2.4 Failure criteria – stability

Failure criteria with respect to stability are given in Sec.6 [7].

2.5 Failure criteria - ultimate stress

2.5.1 Scantlings calculations can also be carried out based on stress instead of strain when laminates are homogeneous through the thickness. Based on the linear relation between stress and strain prescribed in [2.2.1] strain can be converted to stress based on recognized engineering methods or test results on the actual laminates can be used (rule of mixtures for individual plies and laminate theory). Any approximation shall provide results on the conservative side.

Guidance note:

Ultimate stress may be a practical failure criterion when strength data is available in terms of stress only.

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3 Scantling calculation methods

3.1 General

3.1.1 Composites are usually stacked in a certain order to achieve certain properties. This includes balancing a laminate for certain properties or introducing a light weight core as a middle layer between two skin laminates.

Analyses may be based on the stiffness of the laminate or panel expressed as engineering moduli, or strains may be determined from laminate/panel line loads and line moments via the complete stiffness matrix (ABD matrix). Both approaches are acceptable as prescribed in the rules.

3.1.2 Scantlings can be determined by the use of the formulas given in the Sec.6, or by direct calculation or by FEA according [3.3], observing the limitations prescribed in the rules.

3.1.3 Safety factors are specified Sec.6 [7].

3.2 Rule formulas

3.2.1 Rule formulas for the calculation of fibre strain for loaded panels and stiffeners/frames/girders based on engineering laminate moduli are given in Sec.6.

3.2.2 Alternatively to the rule formulas, fibre strain can be calculated directly from laminate line loads and moments using laminate theory (the full stiffness matrix). The same methods as prescribed in Sec.6 shall be used for calculating laminate line loads and moments from the design loads.

3.2.3 Rule formulas given for direct calculation of scantlings for panels, stiffeners, girders etc. apply to approximately orthogonal structural arrangements with a clear hierarchy of structural members. Where this conditions is not fulfilled more comprehensive investigations will be necessary, e.g. grillage analyses.

3.3 Finite element analysis (FEA)

3.3.1 FEA can be used for structural analysis of particular detailed designs, of subassemblies (e.g. to determine plate reactions for non-rectangular shapes, uneven pressure distribution, varying scantlings, etc.) or for global strength of the complete hull and/or superstructure. The load cases prescribed in Ch.3 shall be used as relevant for the particular analyses, as well as other relevant loads.

3.3.2 FEA may be carried out using non-linear geometry, except where proscribed elsewhere in the rules.

FEA may not be carried out using non-linear material properties, except based on special agreement with the Society. LPF analysis based on up-dating of the stiffness matrix is acceptable.

3.3.3 Failure criteria shall be as prescribed in [2]. Allowable strains/stresses and safety factors shall be the same as when the rule formulas are used.

Guidance note:

Software and FEA postprocessors using e.g. Tsai-Wu generate results for first ply failure (FPF) if no updating of the stiffness matrix is carried out. The use of FPF is acceptable. If LPF shall be invoked, the method for assessing FPF based on the analyses results shall be agreed upon with the Society.

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3.3.4 Geometrically non-linear effects for the analysis of structural response of laterally loaded convex curved panels, i.e. where the curvature of the panel is towards the laterally loaded side may not be taken into account when combined with the load cases specified in the rules except as specified in Sec.6.

3.3.5 Global strength analysis using FEA may be challenging with respect to the defining appropriate support conditions, balancing of the FE model and the application of the loads. This may result in a global load distribution differing from the rules values. Thus, results obtained by this analysis need to be scaled to the loads prescribed in Ch.3.

Guidance note:

DNVGL-CG-0138 *Direct strength analysis of hull structures in passenger ships* provide recommendations for the modelling and execution of FEA with respect to global strength.

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SECTION 5 HULL GIRDER (GLOBAL) STRENGTH

1 General

1.1 Introduction

1.1.1 The assessment of the global strength shall, in addition to laminate in-plane strength, also account for buckling capacity of plates and girders/stiffeners under compressive and shear load.

Guidance note:

When hulls and decks are constructed using sandwich plating, the structural material subject to global loads is often much less than for single skin hulls, making global strength more critical.

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2 Hull girder global loads

2.1 Introduction

2.1.1 Global loads are considered loads acting on the hull without the consideration of local load introduction. For slender monohulls, relevant global loads are global vertical shear force and global vertical bending moment. Others (global torque, global transverse shear force, global transverse bending) are relevant to a lower degree and/or for unusual configurations.

2.1.2 Global loads are generally considered to arise through:

— sea loads
— accelerations
— gravitational loads
— others, unspecified (e.g. crane or rig attachments).

2.2 Load cases

2.2.1 Load cases and load definitions to be used for hull girder strength analysis of composite vessels are specified in Ch.3.

3 Structural assessment

3.1 Generic section analysis

3.1.1 The expression hull girder implies that the hull structure will be modelled as a single beam (monohulls) or a grillage of beams (multi-hulls). This will be followed by a generic section analysis which includes the review of the global strength capacity of 2-dimensional beam cross sections.

This is provided the structure allows for such simplification. Should there be doubts, it is preferred to apply methods as described in [3.2].

Guidance note:

A sufficient number of potential critical sections need to be analysed to identify the critical ones. For this purpose it will be required to determine the 2D beam cross section stiffness characteristics:

— EI (for bending analysis)
— GA (for shear analysis)
— GJ (for torque analysis)
— EA (for uniaxial compression/tension).

for the individual hull sections. Only this way, the individual ply, layer, material and orientation characteristics are reflected appropriately within one cross section.

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

3.1.2 Only effective parts of a section may be accounted for when calculating the section properties. This implies including only structures which are structurally continuous through and on either side of the cross section over a length long enough to ensure effective force transfer.

3.1.3 Openings and cut-outs in structures relevant to global strength calculations shall be treated with utmost diligence as they do not only affect the individual section analysed but possibly also neighbouring sections. This shadow effect is however very much depending on the load type (bending/uniaxial load or shear and torque) and also on the laminate type. A generic shadow to assume in case quasi-isotropic structures are subjected to bending or uniaxial tension/compression, is shown in Figure 1. The effective area to account for in proximity of openings and cut-outs of openings is assumed to be reduced by the shaded areas in Figure 1, i.e. inside tangents at an angle of 30° to each other. Example for transverse section III:

$$b_{\mathrm{III}} = b' + b'' + b'''$$

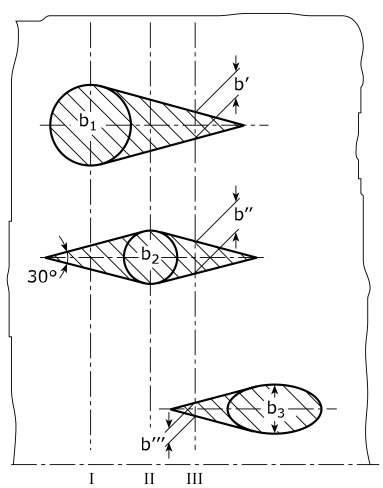

Figure 1 Effect of openings

For twin hull vessels the effective breadth of wide decks without longitudinal bulkhead support will be specially considered by the Society.

3.2 3D global analysis

3.2.1 For structures with a high complexity exceeding the applicability of what is described in [3.1], an appropriate 3-dimensional analysis will be required.

3.2.2 Acceptable methods and procedures of analyzing the structures in 3D are subject to agreement with the Society.

3.3 Safety assessment: allowable stresses/strains

3.3.1 For both methods of hull girder strength global analysis, as per [3.1] and [3.2], allowable stresses/strains and pertinent safety factors shall be used as per Sec.6 [7].

SECTION 6 SCANTLINGS

1 General

1.1 Introduction

1.1.1 The definition of scantling requirements in this section shall be applied in conjunction with the relevant load cases defined in Ch.3 provisions for materials DNVGL-RU-SHIP Pt.2 Ch.4 and the previous and following sections of this chapter. In combination they provide a distinct level of structural reliability.

This generic approach of deriving scantling requirements is based mainly on the application of the classical laminate theory (CLT), the determination of the structural response is based on beam and panel theory and finally the maximum stress and strain concept as the failure criteria.

1.1.2 The provisions in this section are based on a geometrical structural arrangement which features orthogonal structures with a certain structural hierarchy.

1.1.3 The methodology given in this section is presented in successive order.

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

1.1.5 Alternative methods, e.g. FEA, for deriving scantlings to the method presented in this section are given in Sec.4 [3] *Scantling calculation methods*. Such methods may be necessary or favourable for structures in which a clear structural hierarchy as assumed in [1.1.2] is not present, e.g. grids, or not having an orthogonal lay-out. FEA may also be the preferred option by the designer.

2 Elasto-mechanical properties of fibre reinforced thermoset matrix composites

2.1 General

2.1.1 The purpose of this item is to provide methodologies for deriving elasto-mechanical properties of FRP which are required and of primary importance for the ongoing analysis for obtaining scantlings in [3] through [7] of this section.

2.2 Nomenclature

2.2.1 Denotations:

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

$\nu_f 12$ = Poisson's ratio of fibre
ν_m = Poisson's ratio of resin
G_m = shear modulus of the matrix
G_f = shear modulus of the fibre
E_x = Young's modulus of a ply, multiply or laminate in x-direction of global laminate 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 co-ordinate system
Θ = angle of inclination/transformation from local ply coordinate system (1, 2 coordinates) to global laminate coordinate system (x, y coordinates), see Figure 1.

2.2.2 Definitions

Table 1 Definitions

Term	*Definition*
laminate	a general expression for a structural unity, a composition of structural fibres, laid down in a polymer matrix
multiply	in the definition of these rules, 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)
ply	in the definition of these rules, a ply is one laminated layer containing fibre reinforcements aligned in one direction only (unidirectional) or one layer of isotropic or quasi-isotropic material (CSM)
sandwich	laminates containing a lower density sandwich core or other constituents for achieving certain mechanical purposes

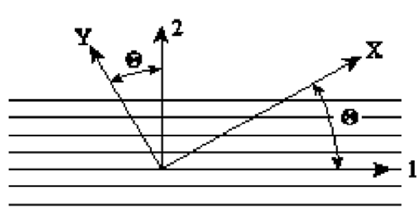

Figure 1 Local single ply and global laminate coordinate systems

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

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

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

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

where:

m_{fi} = single ply areal weight of fibre reinforcements
ψ_i = fibre mass fraction of single ply.

2.3 Single ply basic elastic engineering constants

2.3.1 The basic single unidirectional ply is the level to start with [2.3.2]; subsequently build up to finally result in properties on a full laminate level [2.4], [2.5], [2.6].

2.3.2 A single unidirectional laminated ply consists of long fibres, oriented in one direction, embedded in a polymeric matrix. Typical fibre materials are E-glass, aramid or carbon. Representative material properties of fibre and matrix materials can be found in Table 2. Values presented in this table are for guidance only and need to be confirmed when used for the purpose of designing structures.

The following values are derived for plies containing unidirectional fibres. From those, the properties of multi-axially aligned laminated plies may be derived subsequently, see [2.4] and [2.5]. Chopped strand mats are considered separately below.

2.3.3 *Elastic properties of a single unidirectional ply:*

a) Longitudinal Young's modulus:

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

b) Transverse Young´s modulus:

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

c) Poisson´s ratios:

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

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

d) Shear modulus:

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

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

2.3.4 *Elastic properties of a single chopped strand mat:*

a) Young´s modulus

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

b) Shear modulus

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

Where E_{11} and E_{22} shall be determined like in a) and b), using a fibre volume content appropriate for CSM.

Table 2 Generic constituent material properties

<table>
<tr><td colspan="3" rowspan="2"></td><td colspan="4">Fibres</td><td colspan="2">Matrices</td></tr>
<tr><td>E-Glass</td><td>Aramid</td><td>HS Carbon</td><td>HM Carbon</td><td>Polyester</td><td>Epoxy</td></tr>
<tr><td colspan="2">Specific gravity</td><td>[g/m³]</td><td>2.54</td><td>1.45</td><td>1.77</td><td>1.9</td><td>1.2</td><td>1.2</td></tr>
<tr><td rowspan="2">Young´s modulus</td><td>parallel to fibres</td><td>MPa</td><td>73000</td><td>130000</td><td>230000</td><td>370000</td><td rowspan="2">3000</td><td rowspan="2">3600</td></tr>
<tr><td>perpendicular to fibres</td><td>MPa</td><td>73000</td><td>5400</td><td>14000</td><td>9000</td></tr>
<tr><td colspan="2">Shear modulus</td><td>MPa</td><td>30000</td><td>12000</td><td>23000</td><td>20000</td><td>1140</td><td>1330</td></tr>
<tr><td colspan="2">Poisson´s ratio</td><td>-</td><td>0.18</td><td>0.35</td><td>0.27</td><td>0.23</td><td>0.316</td><td>0.35</td></tr>
</table>

2.4 Single ply stiffness properties

2.4.1 The representative stiffness properties for a single ply that is part of a multiply fabric, a laminate or a sandwich laminate is derived in three steps.

Firstly the stiffness matrix Q will be computed for each ply from its engineering constants in the local coordinate system [2.4.1].

In a second step, the stiffness matrix Q will be transformed to the global coordinate system, resulting in the transformed stiffness matrix Q´ [2.4.2].

From this, the engineering constants of each ply in the global laminate coordinate system will be determined in a third step [2.5].

2.4.2 Single UD ply stiffness matrix in local coordinate system

The components of the stiffness matrix Q are determined for a unidirectional laminated ply as follows:

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

$$Q12 = Q21 = \frac{\nu_{21} \cdot E_{11}}{(1 - \nu_{12} \cdot \nu_{21})}$$

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

$$Q33 = G12$$

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

$E_{11} = E_{22} = E_{CSM}$

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

$G_{12} = G_{CSM}$

Stiffness matrix components Q for cores of a sandwich laminate shall be derived using the above equations, too, using the materials mechanical properties:

$E_{11} = E_x$; $E_{22} = E_y$; ν_{12} ; ν_{21} ; G_{12}

2.4.3 Single UD ply stiffness matrix transformed to global coordinate system

Angle transformation: The following formulae are used to transform elasto- mechanical properties found in [2.4.1] for a unidirectional laminated ply in the local 1, 2 coordinate system to the global x, y coordinate system by an in-plane polar transformation of angle Θ.

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

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

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

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

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

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

$$Q21' = Q12'$$

where:

Θ = angle of transformation

Q' = transformed stiffness matrix of orthotropic layer in global coordinate system.

2.5 Multiply stiffness properties

The multiply is an arrangement with a distinct number of plies of different orientations bi-axial, tri-axial or quadri-axial arrangements.

The stiffness properties of a multiply arrangement 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 multiply will be neglected here by forcing the coupling matrix B to be zero.

2.5.1 Following the classical laminate theory, the ABD_L matrix is the stiffness matrix of the multiply laminate (index M for multiply). The individual matrices are calculated as follows:

Extension matrix A_L:

$$A11_M = \sum_{i=1}^{n} Q11'_i \cdot t_i$$

$$A12_M = A21_M = \sum_{i=1}^{n} Q12'_i \cdot t_i$$

$$A13_M = A31_M = \sum_{i=1}^{n} Q13'_i \cdot t_i$$

$$A22_M = \sum_{i=1}^{n} Q22'_i \cdot t_i$$

$$A23_M = A32_M = \sum_{i=1}^{n} Q23'_i \cdot t_i$$

$$A33_M = \sum_{i=1}^{n} Q33'_i \cdot t_i$$

Bending extension matrix B_L:

All forced to be zero:

$B11_M = B12_M = B13_M = B21_M = B22_M = B23_M = B31_M = B32_M = B33_M = 0$

Bending matrix D_L:

$$D11_M = \frac{1}{3} \cdot \sum_{i=1}^{n} Q11'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D12_M = D21_M = \frac{1}{3} \cdot \sum_{i=1}^{n} Q12'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D13_M = D31_M = \frac{1}{3} \cdot \sum_{i=1}^{n} Q13'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D22_M = \frac{1}{3} \cdot \sum_{i=1}^{n} Q22'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D23_M = D32_M = \frac{1}{3} \cdot \sum_{i=1}^{n} Q23'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

$$D33_M = \frac{1}{3} \cdot \sum_{i=1}^{n} Q33'_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

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

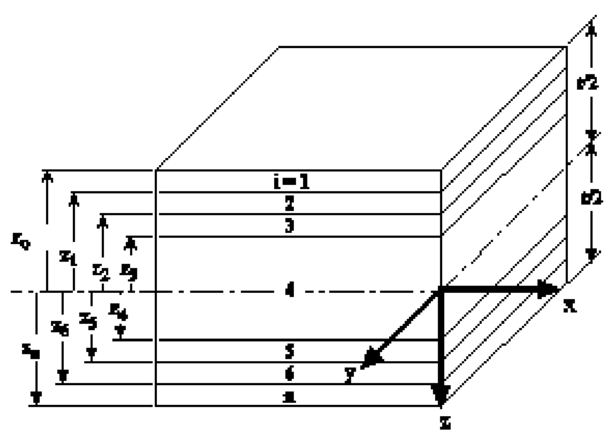

Figure 2 Ply definitions

Resulting in the ABD_M matrix:

$$\begin{bmatrix} A11_M & A12_M & A13_M & 0 & 0 & 0 \\ A21_M & A22_M & A23_M & 0 & 0 & 0 \\ A31_M & A32_M & A33_M & 0 & 0 & 0 \\ 0 & 0 & 0 & D11_M & D12_M & D13_M \\ 0 & 0 & 0 & D21_M & D22_M & D23_M \\ 0 & 0 & 0 & D31_M & D32_M & D33_M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}_M$$

And the inverse ABD_M matrix:

$$\begin{bmatrix} a11_M & a12_M & a13_M & 0 & 0 & 0 \\ a21_M & a22_M & a23_M & 0 & 0 & 0 \\ a31_M & a32_M & a33_M & 0 & 0 & 0 \\ 0 & 0 & 0 & d11_M & d12_M & d13_M \\ 0 & 0 & 0 & d21_M & d22_M & d23_M \\ 0 & 0 & 0 & d31_M & d32_M & d33_M \end{bmatrix} = \begin{bmatrix} a & b \\ b & d \end{bmatrix}_M = \begin{bmatrix} A & B \\ B & D \end{bmatrix}_M^{-1}$$

2.5.2 The following layer stiffness values will be used for buckling analysis in [6.3]:

$$Q11'_M = \frac{A11_M}{t_M} \; ; \; Q12'_M = \frac{A12_M}{t_M} \; ; \; Q22'_M = \frac{A22_M}{t_M} \; ; \; Q33'_M = \frac{A33_M}{t_M}$$

where:

t_M = thickness of a multiply.

2.6 Laminate stiffness properties (including sandwich)

2.6.1 Depending on the structural functionality of a laminate, different stiffness characteristics will be relevant for the further analysis of the structural response on applied load.

These typical stiffness characteristics are:

— tensile/compressive stiffness
— flexural stiffness
— in-plane shear stiffness

and can be described either by the use of the engineering constants for moduli, E*A, E*I or G*A, or also the relevant components of the ABD_M matrix. It is depending on the demands, which of those alternative stiffness properties will be sophisticated/effective in analysis and use.

2.6.2 In-plane engineering constants

In-plane engineering constants (through-thickness averaged) of a single skin laminate or a complete sandwich laminate (index L for laminate) with individual stacking sequence and global x,y coordinate system, provided that the full laminate is considered being one multiply:

$$E_{xL} = \frac{1}{t_M \cdot a11_M} \; ; \; E_{yL} = \frac{1}{t_M \cdot a22_M} \; ; \; G_{xyL} = \frac{1}{t_M \cdot a33_M} \; ; \; \nu_{xyL} = -\frac{a12_M}{a11_M}$$

2.6.3 In-plane stiffness properties

In-plane stiffness properties (shear, tension, compression) of a single skin laminate or a complete sandwich laminate with individual stacking sequence is determined by the extension matrix $[A]_L = [A]_M$, provided that the full laminate is considered being one multiply.

2.6.4 Flexural stiffness of single skin laminate

Flexural stiffness of a single skin laminate with individual stacking sequence is determined by the extension matrix $[D]_L = [D]_M$, provided that the full laminate is considered being one multiply.

2.6.5 Flexural stiffness of sandwich laminate

The flexural stiffness of a sandwich laminate with individual stacking sequence is determined by the bending stiffness matrix $[D]_L = [D]_M$, provided that the full laminate is considered being one multiply.

Alternatively, the flexural stiffness can be determined in the following simplified way:

$$D11 = \sum E_{xLi} \cdot \left(\frac{t_i^3}{12} + t_i \cdot e_i^2 \right) = EI_x$$

$$D22 = \sum E_{yLi} \cdot \left(\frac{t_i^3}{12} + t_i \cdot e_i^2 \right) = EI_y$$

$$D33 = 0$$

where:

$E_{xLi/yLi}$ = Young´s modulus of sandwich layer *i* in relevant direction
t_i = thickness of layer *i*
e_i = distance of layer *i* centroid from neutral axis of sandwich.

3 Laterally loaded plates

3.1 Introduction, applicability

3.1.1 In the following, 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.

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

3.1.3 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. Should this be the case, individual treatment is required.

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.

3.1.4 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.

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

3.2 Plate parameters

3.2.1 Laminated plates shall be characterized by the following parameters:

3.2.2 Structural parameters

T_c = thickness of sandwich core

Z_i = distance from a certain location to the neutral axis.

3.2.3 Geometrical parameters

The unsupported panel span is in general to be measured between the effective centres of the supporting members, as indicated in Figure 3 below. The unsupported span can be taken as the inside distance between the stiffeners provided the design pressure is calculated based on the same span (applicable to bottom slamming loads).

s_x = unsupported span in global x-direction

s_y = unsupported span in global y-direction.

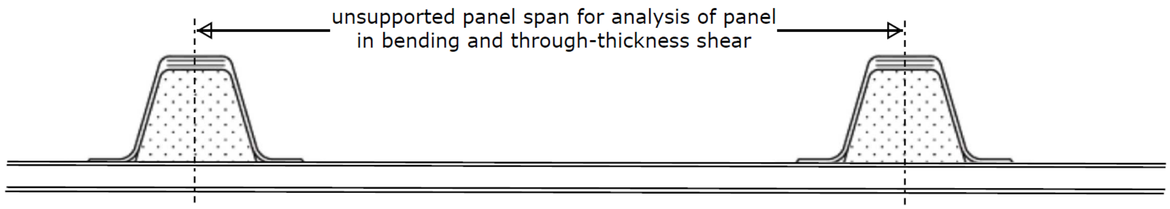

Figure 3 Definition of panel span

The geometric aspect ratio is:

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

3.2.4 Effective aspect ratio and effective span

For the purpose of determining scantlings for panels it is required to determine the effective span s_{eff}, according to which major bending and shear loads are calculated from:

For orthotropic panel properties with D11 not equal D22, the geometrical aspect ratio ar_g needs to be corrected:

$$ar_{corr} = ar_g \cdot \sqrt[4]{\frac{D22}{D11}}$$

And for cases in which the analysis is not fully based on CLT:

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

S_{eff} = S_y if ar_{corr} is > 1,

the effective span runs in y-direction and is similar with the geometrical short span, and:

S_{eff} = S_x if ar_{corr} is < 1 and $ar_{eff} = 1/ar_{corr}$,

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

3.2.5 Edge support boundary conditions

Usually, all four (4) sides of panels are supported. The following discrete conditions are possible:

- all edges fixed (continuous panels with similar spacing substructures)
- all edges simply supported (non-continuous panels or unclear situations)
- all edges partially fixed (continuous panels subject to slamming pressures, with identical or near identical spacing to panel stiffness ratio s_{eff}^2/EI of adjacent panels.

The choice depends on geometrical and structural situations and can be refined using appropriate methodologies, subject to agreement by the Society.

The relevant coefficients are provided in Table 3 and are processed within items [3.3.5].

3.2.6 Alternate boundaries, corrected span; hard chines

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 ω shall be close to 90° to allow for such assumption, see Figure 4. 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.

Boundary conditions as per normal panel analysis can be chosen.

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

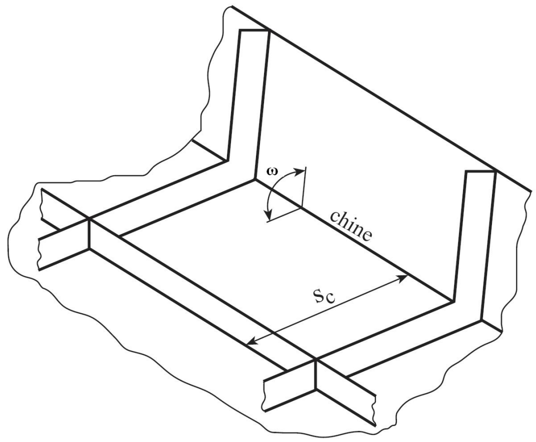

Figure 4 Corrected span

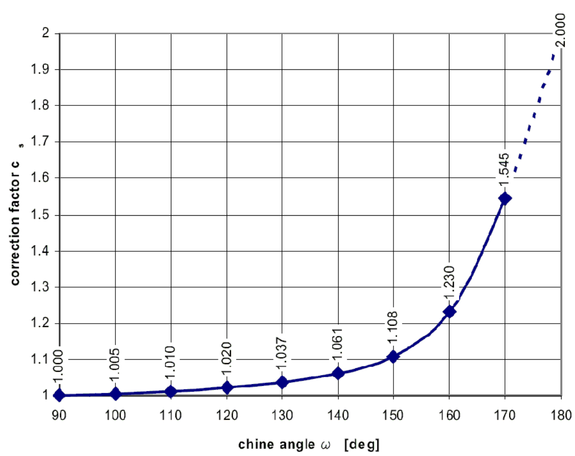

Figure 5 Panel span correction factor c_s dependant on chine angle

This correction is particularly applicable for equidistant spacing 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 Figure 5.

3.2.7 Alternate boundaries, corrected span; virtual chines

Guidance note:

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 athwardships 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.

c) The suitability of this approach might not cover all occurring variants of design and in doubt will need to be confirmed by DNV 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

Figure 6, this division produces two (2) virtual chines (Ps and Stb) and thus three (3) panels, one of them across centreline. With the existence of a centreline -or two slightly off centreline girders Figure 7, the method provides two (2) panels each Ps. and Stb. between the girder and the gunwhale.

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

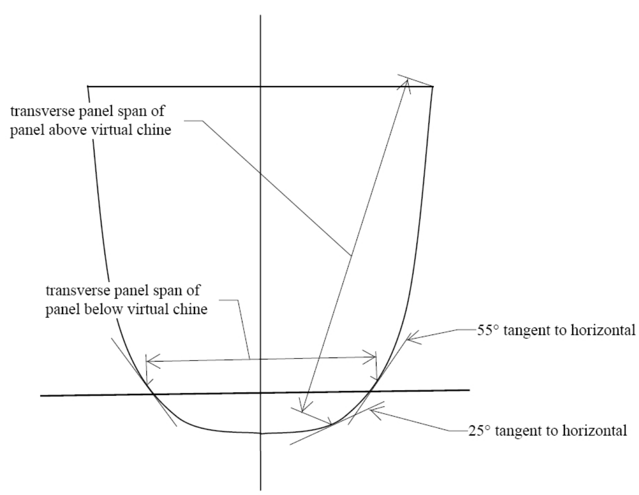

Figure 6 Panel span with no longitudinal girders

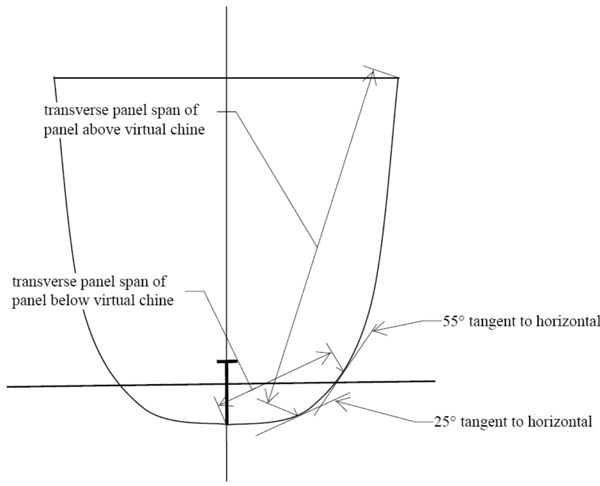

Figure 7 Panel span with existence of longitudinal girder

3.2.8 Curvature reduction

Curvature will only be considered if the plate is curved in the direction of the effective span s_{eff}, see Figure 8.

Plate curvature correction coefficient:

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

where:

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

and:

$r_{c,min} \;=\; 0.65$

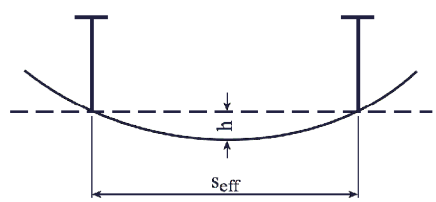

Figure 8 Plate curvature

3.3 Plate reactions

3.3.1 In the following, methodologies are provided for the case that sandwich and single skin panels have consistent scantlings and uniform lateral pressure across their area. Should this not be the case, reactions shall be determined for additional locations other than those described in [3.3.5] and [3.3.4]. Loading of a panel other than a uniform pressure requires an equivalent or separate approach.

Restrictions, limitations and assumptions of this methodology are described in [3.1].

3.3.2 For single skin panels, membrane effects may be included if the panel has sufficient in-plane support along all edges. In such a case a detailed analysis shall be carried out taking properly into account the in-plane and bending stiffness of the panel, the rotational stiffness and stiffness in the plane of the panel of the supporting stiffeners/girders and the adjoining panels. The analysis shall be detailed enough to quantify all stress concentrations along the panel edges.

3.3.3 The plate reactions determined in this item/paragraph are basis for further evaluation in [5].

3.3.4 Reaction bending moment

For most material combinations and unless the laminates do not have consistent layup and/or properties across the panel, the maximum reaction bending moment of a plate panel emerges:

— at the panel edges adjacent to the effective span for a panel with all edges clamped
— at the center of a panel for a panel with all sides simply supported
— both at the center and at the edges for a panel with partially fixed edges:

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

where:

β	=	see Table 3
p_d	=	lateral design pressure on associated plating according to Ch.3
s_{eff}	=	effective panel span according to [3.2.4]
r_c	=	curvature correction coefficient, see [3.2.7].

3.3.5 Reaction shear force

The maximum shear force reaction, occurring as a line force, emerges at the center of the panel edges which are adjacent to the effective panel span, see Figure 9:

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

where:

γ	=	see Table 3
p_d	=	lateral design pressure on associated plating according to Ch.3
s_{eff}	=	effective panel span.

Should a sandwich panel be constructed using a core with different shear strength properties in different directions (e.g. honeycomb), the secondary maximum shear reaction line force has to be determined. This force occurs at the panel edges spanning parallel to the effective span, see Figure 9.

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

where:

γ_t	=	see Table 3.

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

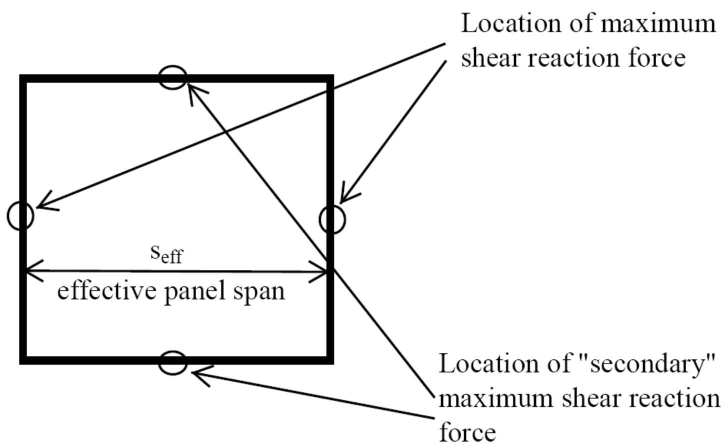

Figure 9 Locations of maximum shear reaction line forces

Table 3 Values β, α, γ,

For panel with all sides simply supported									
ar_{eff}	1	1.2	1.4	1.6	1.8	2	3	4	5	∞
β	0.29	0.38	0.45	0.52	0.57	0.61	0.71	0.74	0.74	0.75
α	0.04	0.06	0.08	0.09	0.10	0.11	0.13	0.14	0.14	0.14
γ	0.42	0.46	0.48	0.49	0.50	0.50	0.51	0.50	0.50	0.50
γ_t	0.42	0.39	0.36	0.35	0.34	0.34	0.34	0.34	0.34	0.34
For panel with all sides partially clamped										
ar_{eff}	1	1.2	1.4	1.6	1.8	2	3	4	5	∞
β	0.27	0.31	0.35	0.39	0.42	0.43	0.43	0.43	0.43	0.43
α	0.03	0.04	0.05	0.06	0.06	0.07	0.08	0.08	0.09	0.09
γ	0.42	0.46	0.48	0.49	0.50	0.50	0.51	0.50	0.50	0.50
γ_t	0.42	0.39	0.36	0.35	0.34	0.34	0.34	0.34	0.34	0.34
For panel with all edges clamped										
ar_{eff}	1	1.2	1.4	1.6	1.8	2	3	4	5	∞
β	0.31	0.38	0.44	0.47	0.49	0.50	0.50	0.50	0.50	0.50
α	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
γ	0.42	0.46	0.48	0.49	0.50	0.50	0.50	0.50	0.50	0.50
γ_t	0.42	0.39	0.36	0.35	0.34	0.34	0.34	0.34	0.34	0.34

4 Laterally loaded beams

4.1 Introduction, applicability

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

4.1.2 Typically, beams consist of one or more webs designed to carry the shear force and flanges to carry the bending load. 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.

4.1.3 Beams should be designed in a way that the transfer of loads is fibre dominant. In general this will require shear webs to include fibre in the +/- 45° direction, whereas the flanges consist dominantly of 0° plies. It shall be ensured that shear loads are transferred efficiently to the flange and plating.

4.1.4 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 analytical model is presented by a simple beam with appropriate support conditions.

4.1.5 In case the scantlings and loads 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 clamped
— bending moment at the center of the beam and shear effects at the end of the beam for a support condition - ends simply supported
— bending moment at the center and end of the beam and shear effects at the end of the beam for a support condition - one end clamped and one end simply supported.

Should scantlings and/or loading not be constant or uniform along the beam, bending moments and shear forces need to be determined individually and more locations than indicated above will be required to be analysed.

4.1.6 It is recommended to use symmetrical or near-symmetrical section shapes (symmetry axis normal to the lateral pressure plane, i.e. plating), 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.

4.1.7 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 normal to the plating.

4.2 Beam parameters

4.2.1 A beam is composed of a plurality of different functional elements, most often:

— web
— flange
— attached plating.

4.2.2 Structural parameters

a) Flexural stiffness:

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

where:

E_i = Young´s modulus of element *i*, according to [2.6.2] a)
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.

b) Shear stiffness:

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

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

where:

t_i = web thickness
h_i = depth of web measured perpendicular to associated plating, see Figure 12
G_i = in-plane shear modulus of element *i*, according to [2.6.2] a).

4.2.3 Geometrical parameters

l = unsupported length of the beam
s = stiffener or girder spacing as per Ch.3.

4.2.4 Effective width of plating

The expression effective width or effective flange is used to describe the effect in which a stiffener or a girder mounted on a large panel receives some contribution in a way the panel acts as a lower flange to the stiffener.

The method can be adopted for single skin as well as for sandwich panels.

The method is for beams with a constant lateral load, but can be used with reasonable accuracy also for beams with single point load(s). Other load scenarios are subject to agreement by the Society.

For means of analytical calculation, the effect is simplified in a way that an effective width of the panel is determined which is supposed to result in a similar bending strain (constant across this width) compared to what is expected as a peak maximum in reality (see guidance note).

The stiffener/girder cross section shall be built up as a composite beam with layers representing the width, thickness and modulus for each of the skins, webs and cap. The width of the inner and outer skins shall both be set equal to the width found from the formula for the width of the effective flange given for stiffened single skins taking into consideration the difference in width at midspan and at the ends. Effective width may include tabbing and pad layers. The stiffener/girder with associated panel is analysed as an Euler-Bernoulli beam applying bending moments in accordance with the relevant rule formulas.

The effective width shall be calculated as follows:

$$b_{eff} = \frac{1}{1 + 3.3 \cdot \frac{E}{G} \cdot \left(\frac{b}{2 \cdot l^*}\right)^2} \cdot b + w_f$$

where:

b_{eff} = effective width of flange
b = c-c distance between the stiffeners or girders in adjacent fields
E = E modulus of panel laminate in the beam direction
G = shear modulus of panel laminate
w_f = foot width of girder, see Figure 10
w_p = width of pad layer Figure 10
$l*$ = length between moment inflexion points i.e. zero bending moments, see Figure 11.

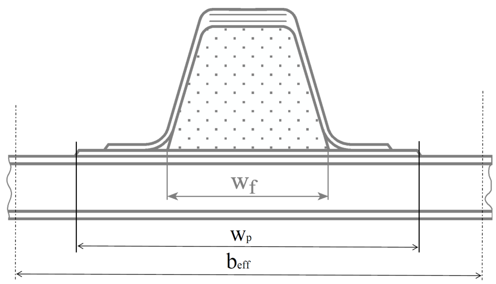

Figure 10 Beam definitions for effective width

Figure 11 Samples in the following are typical distributions of bending moments depending on the pertinent boundary conditions, together with the relevant distance between inflexion points i.e. points of zero bending moments.

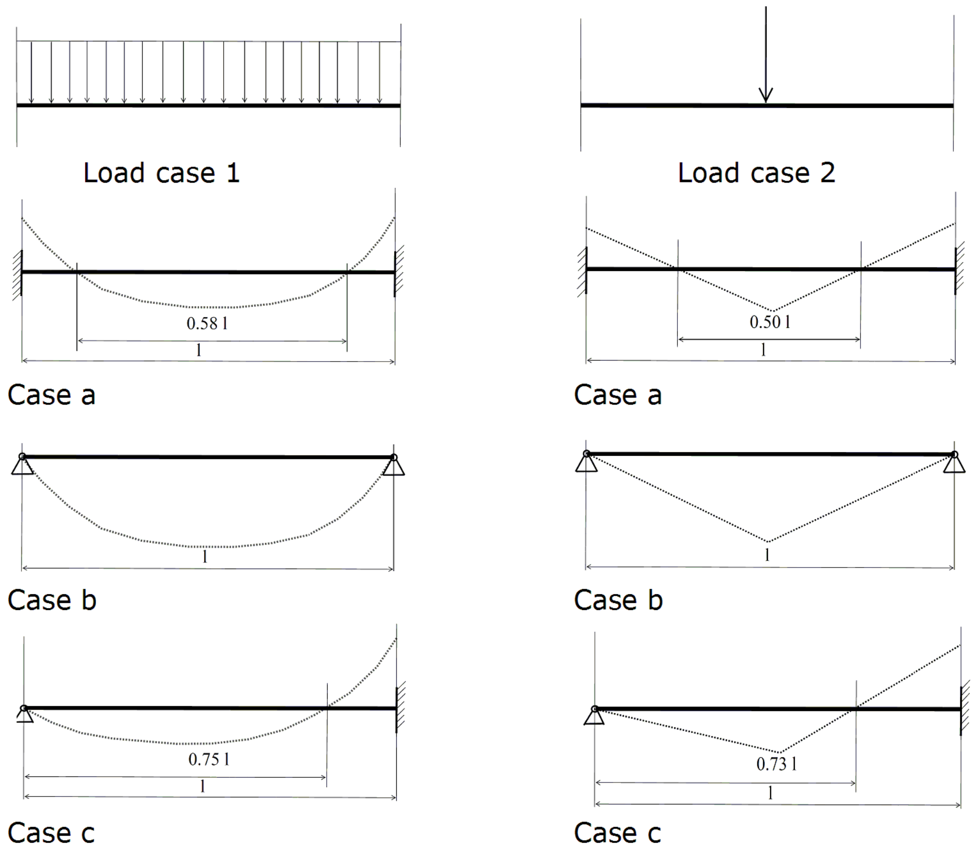

Figure 11 Distance between zero bending moments (dashed line) for different boundary conditions of beams under constant lateral load (load case 1) and for central single point load (load case 2)

Inflexions of the field moments can be taken from Figure 11 and from the Table 4 below. Inflexions for the (fixed) boundaries shall be calculated as being mirrored across the boundary, or as per Table 4.

Other load cases can be calculated in a similar manner but require agreement by the Society.

Table 4 Inflexion point distances l* for beam under constant lateral load and central point load

		l length between zero bending moments*				
		boundary condition in rotation	*at boundary*	*in field*	*in boundary*	*boundary condition in rotation*
Load case 1	Case a	fixed	0.42 l	0.58 l	0.42 l	fixed
	Case b	free		1.0 l		free
	Case c	free		0.75 l	0.50 l	fixed
Load case 2	Case a	fixed	0.50 l	0.50 l	0.50 l	fixed

		l* length between zero bending moments				
		boundary condition in rotation	*at boundary*	*in field*	*in boundary*	*boundary condition in rotation*
	Case b	free		1.0 l		free
	Case c	free		0.73 l	0.54 l	fixed

Guidance note:

This approach does not constitute a stringent and correct analysis of such beams on sandwich panels. The underlying assumption of the beam responding as an Euler-Bernoulli beam is not correct, to a smaller or lesser degree, and the assumption of equal width of the effective flanges of the inner skin and outer skin is not correct. However, this approach is acceptable to the Society as a simplified approximate method as it has been found to give acceptable results on the conservative side by comparison with results from FEA analyses of a number of sandwich/stiffener configurations.

Alternative methods:

The strain level in sandwich panels with associated stiffeners/girders loaded by a lateral pressure can be determined either by a FEA of a representative model or by using the approximate approach.

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

4.2.5 Beam depth

Where beams are inclined towards the attached plating, see Figure 12, the inclination shall be considered in an appropriate way when calculating the scantlings. Usually the web of a beam is contributing to the full depth of the beam, where the bending stiffness shall account only for a structural height as measured perpendicular to the attached plating.

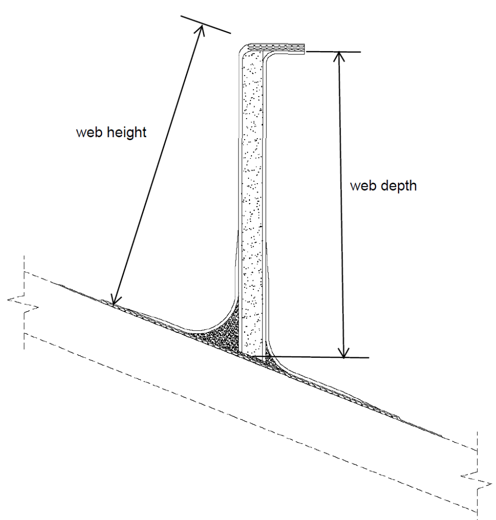

Figure 12 Inclined stringer

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

4.2.6 Edge support boundary conditions

The following discrete conditions are possible:

— both ends fixed (continuous beams with similar l^2/EI of adjacent beams)
— both ends simply supported (non-continuous beams or unclear situations)
— one end fixed, one end simply supported
— ends partially fixed upon special considerations (continuous beams subject to slamming pressures; with identical or near-identical effective length to beam stiffness ratio l^2/EI of adjacent beams.

The choice depends on geometrical and structural situations and can be refined using appropriate methodologies, subject to agreement by the Society. The relevant coefficients are given and processed within items [4.3].

4.2.7 Curvature correction

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

where:

$0.03 < \frac{h}{l} < 0.1$

and:

$r_{cb,min}$ = 0.65
.

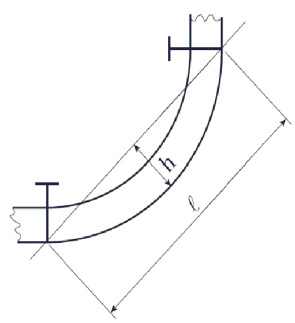

Figure 13 Beam curvature definitions

4.3 Beam reactions

4.3.1 In the following, methodologies are provided for the case that beams have consistent scantlings and uniform load along their length. Should this not be the case, reactions shall be determined for locations other than those described in [4.1.5].

Restrictions, limitations and assumptions of this methodology are described in [4.1].

Beam reactions may have to be determined by FEA, particularly for:

a) orthogonal girder systems with beams of similar stiffness, i.e. to determine grillage effects
b) non-constant lateral pressure
c) arying scantlings along beam.

The plate reactions determined in this item/paragraph are basis for further evaluation in [7].

4.3.2 Reaction bending moment

For most material combinations and unless the beam does not have consistent layup and/or properties along its span, the maximum reaction bending moment of a beam emerges:

— at the ends with both ends clamped
— at the center of a beam with all ends simply supported
— at the clamped end when one side is simply supported and other end is clamped.

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

where:

p_d = lateral design pressure on associated plating according to Ch.3
w = load width
ℓ = length of beam between supports
r_{cb} = beam curvature correction coefficient according to [4.2.6]
c_b = boundary condition coefficient
= 12 for fixed end supports, used for continuous girders, similar length
= 8 for ends simply supported, used for non-continuous girders
= 8 for one end simply supported and other end fixed, used where relevant
= 18 at ends for continuous beams subjected to slamming see [4.2.4]
= 14 at midspan for continuous beams subjected to slamming see [4.2.4].

4.3.3 Reaction shear force:

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

$$F_{q-\max} = \frac{p_d \cdot \ell \cdot w \cdot c_b}{2}$$

where:

p_d = see Ch.3
ℓ = see [4.2.2]
w = see [4.2.2]
c_b = boundary condition coefficient
= 1 for both ends with similar support condition
= 1.25 for clamped end of beam with one side clamped and one side simply supported
= 0.75 for simply supported end of beam with one side clamped and one side simply supported.

5 Structural response, load effects

The following paragraph provides a methodology for the assessment of stresses and strains within laterally loaded structures.

5.1 Panels

5.1.1 Laminate strains of solid or sandwich laminates

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

The required items for the coupling matrix shall be defined as follows:

$$[B] = \frac{1}{2} \cdot \Sigma [Q']_k \cdot \left(z_k^2 - z_{k-1}^2 \right)$$

The following matrix is combining the inverse stiffness matrix and the load matrix:

$$\begin{bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} = \begin{bmatrix} a11_L & a12_L & a13_L & b11_L & b12_L & b13_L \\ a21_L & a22_L & a23_L & b21_L & b22_L & b23_L \\ a31_L & a32_L & a33_L & b31_L & b32_L & b33_L \\ b11_L & b12_L & b13_L & d11_L & d12_L & d13_L \\ b21_L & b22_L & b23_L & d21_L & d22_L & d23_L \\ b31_L & b32_L & b33_L & d31_L & d32_L & d33_L \end{bmatrix} \cdot \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix}$$

where:

$\varepsilon_{x0}, \varepsilon_{y0}, \gamma_{xy0}$ = the resulting strains only from in-plane forces N_x, N_y, and N_{xy}; tension, compression and in-plane shear.

k_x, k_y, k_{xy} = the warpings only from bending moments M_x, M_y, and M_{xy}.

Overall individual strains in a laminate from a combined loading can be determined:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{bmatrix} + z_i \cdot \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

where:

Z_i = location of interest; distance from laminate geometrical mid-plane (not neutral axis) desired strain.

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 mid-plane at each side of the plate, see Figure 2.

Alternatively, the strain in the fibre direction in individual plies can be determined directly from N_x, N_y, N_{xy}, M_x, M_y, and M_{xy} via laminate theory.

The calculated strains in a laminate or in the fibre direction in an individual ply shall not exceed the allowable strains defined in [7].

5.1.2 Shear stresses of sandwich core from shear forces
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:

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

where:

F_q = see [3.3.5]
= $F_{q\text{-}max}$ for core evaluation along effective panel span
= $F_{q\text{-}sec}$ for core evaluation across effective panel span
t_c = core thickness
t_{s1}, t_{s2} = thickness of skins.

The calculated stress may not exceed the allowable defined in [7].

5.1.3 Reaction lateral deflection

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

where:

α = see Table 3
p_d = lateral design pressure on associated plating according to Ch.3
s_{eff} = effective panel span according to [3.2.4]
D_{eff}, EI_{eff} = plate bending stiffness relevant for the direction of the effective panel span.

Guidance note:
The deflections calculated may underestimate real deflections as they do not include the effect of the so-called shear deflection.

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

The maximum allowable deflection is defined in [7].

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

5.2.1 Uniaxial strains in beams from bending
Resulting bending strains at a distance of e_i from the beam's neutral axis:

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

where:

M_{bmax} = reaction bending moment determined in [4.3.2]
EI = effective beam stiffness incl. effective width determined in [4.2]
e_i = distance from beam´s neutral bending axis.

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

Alternatively, the strain in the fibre direction in individual plies can be determined directly from the line loads and moments on the individual laminates, N_x, N_y, as a result of $M_{b\text{-}max}$ via laminate theory.

The calculated strains in a laminate or in the fibre direction in an individual ply shall not exceed the allowable strains defined in [7].

5.2.2 In-plane shear strain in beam webs

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

where:

$F_{q\text{-}max}$ = reaction shear force determined in [4.3.3]
GA = shear stiffness of web determined in [4.2.1].

The calculated strains shall not exceed the allowables defined in [7].

Alternatively, the strain in the fibre direction in individual plies can be determined directly from the line shear load on individual laminates, N_{xy}, as a result of $F_{q\text{-}max}$ via laminate theory.

The calculated strains in a laminate or in the fibre direction in an individual ply shall not exceed the allowable strains defined in [7].

5.2.3 Reaction lateral deflection

The maximum lateral deflection of a beam under symmetrical load can be calculated as follows:

For a beam under line load resulting from pressure on adjacent panel:

$$z_{\max} = \frac{p_d \cdot s \cdot \ell^4 \cdot c_{dp}}{384 \cdot EI}$$

For a beam under centric single force:

$$z_{\max} = \frac{F \cdot \ell^3 \cdot c_{ds}}{768 \cdot EI}$$

where:

p_d = see Ch.1
F = single force
ℓ = see [4.2.2]
s = see [4.2.2]
c_{dp} = boundary condition coefficient

= 1 for fixed end supports
= 5 for simply supported
= 2.1 for one end simply supported and other end clamped

c_{ds} = boundary condition coefficient
= 4 for fixed end supports
= 16 for simply supported
= 7 for one end simply supported and other end clamped.

Guidance note:

The deflections calculated may underestimate real deflections as they do not include the effect of the so-called shear deflection.

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

The maximum allowable deflection is defined in [7].

6 Stability and buckling

6.1 Principles

6.1.1 Composite structures need to undergo special stability evaluations to prove that pertinent failures in different forms will not occur. Typically the most critical buckling modes are the global buckling of a panel and face wrinkling of the skins of a sandwich. To cope with this, analytical approaches are offered in the following. Buckling modes like shear crimping and face dimpling are less likely to occur but need to be evaluated in addition, should facings or cores be of uncommon type or configuration.

6.2 Skin wrinkling of sandwich skins

6.2.1 Skin wrinkling of sandwich skins shall be considered in cases where a sandwich panel is subjected to loadings so that at least one skin is in compression. Depending on the stiffness of the laminate in the relevant direction and on the supporting properties of the core, the following approach is used to assess strains above which skin wrinkling is expected.

6.2.2 Critical wrinkling strain for sandwich with solid, isotropic cores like foam:

$$\varepsilon_{sw-crit} = k_1 \cdot \frac{\left(E_{bf} \cdot E_c \cdot G_c\right)^{\frac{1}{3}}}{E_f}$$

Critical wrinkling strain for sandwich cored with honeycomb:

$$\varepsilon_{sw-crit} = k_2 \cdot \frac{\left(E_{bf} \cdot E_c \cdot \frac{t_f}{t_c}\right)^{\frac{1}{2}}}{E_f}$$

where:

E_{bf} = skin laminate flexural modulus relevant to direction of compression. Thus, care shall be taken for laminate stacks of only few layers of alternating fibre direction. For skins made of many layers providing balanced through thickness elastic properties, a mean compressive Young’s modulus may be adopted instead

E_f = skin laminate tensile (compressive) modulus
E_c = core's Young's modulus in compression
G_c = core's shear modulus
t_f = thickness of skin
t_c = thickness of core
k_1 = 0.5
k_2 = 0.6.

6.3 Buckling of orthotropic plates under membrane loads

6.3.1 Considerations and limitations

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

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

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

where os and is are indices for outer skin and inner skin. Also, all edges need to be supported. There is no implementation for the possibility to calculate plates with one free edge. This condition presumes that there will be no or only minor coupling between in-plane and out-of-plane effects.

6.3.2 Critical buckling strains for panel under uni-axial in-plane compression

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

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

where:

$E_{a\text{-}mean}$ = mean Young's modulus in load direction (a) of full laminate (including core)
t_{tot} = total thickness of full laminate (including core)
b = plate width perpendicular to load direction
a = plate width parallel to load direction
k_x = buckling coefficient
= $h(\overline{\alpha}) + q \cdot \beta$
q = boundary condition adjustment factor
= 2 for unloaded edges simply supported
= 2.36 for unloaded edges clamped
$h(\overline{\alpha})$ = see Figure 14 Simplified $h(\overline{\alpha})$ curves
= modified aspect ratio
= $\frac{a}{b} \cdot \sqrt[4]{\frac{D22}{D11}}$
β = Seydel orthotropic parameter
= $\frac{D12 + 2 \cdot D33}{\sqrt{D11 \cdot D22}}$

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Coefficients from the laminate's bending matrix D:

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

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

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

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

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 [2.5.2].

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

Maximum allowable strains under design load is the critical buckling strain as calculated above, divided by the relevant safety factor as defined in [7.2.5].

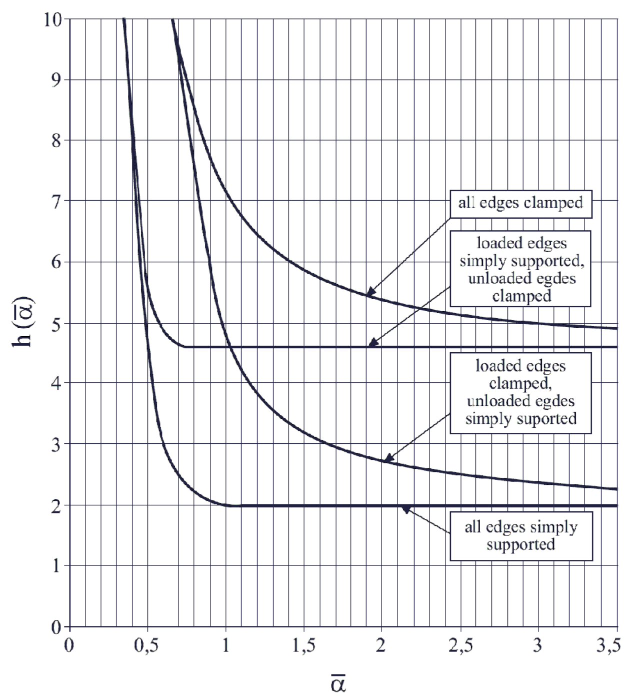

Figure 14 Simplified $h(\overline{\alpha})$ curves

6.3.3 Critical buckling strains for panel under in-plane shear

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

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

where:

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

t_{tot} = total thickness of full laminate

s = plate width *a* or *b*, see below

k_s = buckling coefficient, as per Figure 16

β = "Seydel" orthotropic parameter

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

α = modified inverse aspect ratio

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

If $\alpha \leq 1$, then:

s = *b*

D_a = D11

D_b = D22

If $\alpha > 1$, then

α = $\overline{\alpha}$

s = *a*

D_a = D22

D_b = D11

b = plate width in X,1 direction according to Figure 15

a = plate width in Y,2 direction according to Figure 15.

Maximum allowable strains under design load is the critical buckling strain as calculated above, divided by the relevant safety factor as defined in [7.2.5].

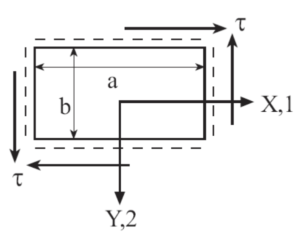

Figure 15 Nomenclature

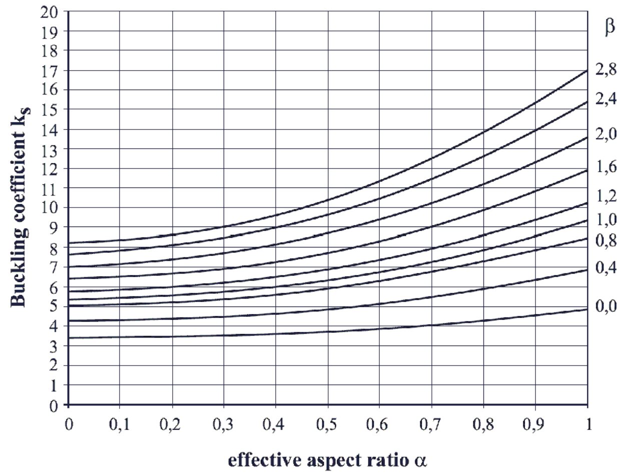

Figure 16 Buckling coefficient k_s

6.4 Buckling of beams, girders, stringers

6.4.1 Beams, girders, stringers etc. shall be analysed with respect to global buckling due to axial compression. The flanges and webs shall be analysed with respect to local buckling due to axial load, bending moment and shear load.

6.4.2 For closed section beams with adequate stiffness or support with respect to tripping, the critical axial global buckling load is given by:

$$P_a = \frac{\pi^2}{l^2} \cdot \frac{D}{\left(1 + \frac{\pi^2 D}{l^2 D_Q}\right)}$$

where:

D = bending stiffness of the beam with associated plating, EI (Nmm^2)
l = the free span of the beam (mm)
D_Q = $t_w\, h_w\, G_w$ (Nmm^2)
t_w = combined thickness of stiffener web(s) (sum of all web thicknesses) (mm)
h_w = height of the beam web (mm)
G_w = shear modulus of the beam web (MPa).

Maximum allowable compressive design load is the critical compressive force as calculated above, divided by the relevant safety factor as defined in [7.2.5].

6.4.3 The critical axial stress in the top flange of top-hat cross sections not supported by a structural core can be calculated as for single skin panels.
The fitting of tripping brackets may be required by the Society.

6.4.4 The critical shear strain with respect to shear buckling in the webs of stiffeners may be calculated according to [6.3].

Maximum allowable strains under design load is the critical buckling strain as calculated above, divided by the relevant safety factor as defined in [7.2.5].

6.5 Buckling of stiffened plate field

6.5.1 Stiffened plate fields can be analysed using formulas developed for such structures fabricated from steel according to Ch.4 provided conservative assumptions are made regarding the stiffness of cross sections of stiffeners and plating are made.

6.6 Buckling of composite columns

6.6.1 All supporting columns made of composites shall be checked on their buckling capacity by using simple Euler theory of linear buckling, applying a safety factor as given in [7.2.5].

6.7 Buckling of steel and aluminium pillars

6.7.1 The cross sectional area of members subjected to compressive loads is not to be less than:

$$A = \frac{10P}{\eta\sigma_c} \text{ (cm}^2\text{)}$$

where:

h = $\frac{k}{\left(1 + \frac{l}{i}\right)}$ minimum 0.3

P = axial load in kN as given for various strength members in [2.2.2] and [2.2.3]. Alternatively, *P* may be obtained from direct stress analysis

l = length of member in m

i = radius of gyration in cm

k = 0.7 in general

= 0.6 when design loads are primarily dynamic

s_c = σ_E when $\sigma_E < \frac{\sigma_F}{2}$ (N/mm^2)

= $\sigma_F\left(1 - \frac{\sigma_F}{4\sigma_E}\right)$ when $\sigma_E > \frac{\sigma_F}{2}$

s_E = $\pi^2 E\left(\frac{i}{100l}\right)^2$ (N/mm^2)

s_F = minimum upper yield stress of material

E = modulus of elasticity for steel = 210 000 MPa, for aluminium = 70 000 MPa.

The formula given for s_E is based on hinged ends and axial forces only.

If, in special cases, it is verified that one end can be regarded as fixed, then the value of s_E may be multiplied by two (2).

If it is verified that both ends can be regarded as fixed, the value of s_E may be multiplied by four (4).

In case of eccentric force, additional end moments or additional lateral pressure, the strength member shall be reinforced to withstand bending stresses.

6.8 Pillars in tanks

6.8.1 Hollow pillars are not accepted within fuel tanks.

6.8.2 Where the hydrostatic pressure may give tensile stresses in the pillars and cross members, their sectional area is not to be less than:

$$A = 0.07 \cdot A_{dk} \cdot p_t \ (\text{cm}^2)$$

(The formula may be used also for tension control of panting beams and cross ties in tanks.)

where:

A_{dk} = deck or side area in m^2 supported by the pillar or cross member
p_t = design pressure, p in kN/m^2 giving tensile stress in the pillar.

Doubling plates at ends are not allowed.

7 Design rules

7.1 Assessment concept

7.1.1 Within this section, the assessment of structural reliability is performed using the failure ratio concept. This concept implies the criteria as per [7.1.1] and [7.1.2].

The failure ratio concept may solely be used in association with the provisions described and defined so far, thus will not automatically be applicable for different methodologies or different load definitions.

7.1.2 Maximum strain criteria

The maximum strain criteria is applicable for all aspects of assessing strength and stability of laminates. It is providing an appropriate measure for fibre reinforced composites under the condition that the composite shows a fibre-dominant load transfer. The defined limits provide a sufficient margin over interlaminar micro cracking and fibre failure in all in-plane directions and are considered providing sufficient structural reliability.

7.1.3 Maximum stress criteria

The maximum stress criteria is applicable for all aspects not covered by [7.1.1], such as sandwich core strength, laminate strength when calculated in accordance with Sec.4 [2.5], bonding strength, interlaminar shear and other matrix-dominant failure modes.

7.2 Allowable strains/stresses

7.2.1 The failure ratio concept includes the definition of maximum allowable stresses and strains. Ratios are being defined for sufficient strength and stability.

7.2.2 Stresses/strains derived in accordance with the provisions in these rules shall not exceed the values given by the following equation:

$$\sigma \text{ or } \tau \text{ or } \epsilon \text{ or } \gamma = \frac{F_r}{R \cdot c_c \cdot c_{rm}}$$

where:

F_r = reference mechanical strength/resistance as per [6], [7.2.3] and [7.2.4]
R = reserve factor [7.2.5]
C_c = reduction factor; only to be used in association with reserve factors for laminates and matrix dominant behaviour, the first two categories of Table 9
= 0.8 for watertight bulkhead structures under hydrostatic load in damaged condition
= 1.0 otherwise and for other structures
C_{rm} = reduction factor; only to be used in association with reserve factors for laminates and matrix dominant laminate behaviour, the first two categories of Table 9
= 0.90 for vacuum assisted production (VARTM, pre-preg)
= 1.0 otherwise.

7.2.3 Laminates - reference mechanical strength/resistance

The allowable stresses and/or strains for laminates are related to on their reference mechanical strength.

Two different approaches are acceptable:

— reference mechanical strength/resistance is represented by the ultimate strength, determined by testing
— reference mechanical strength/resistance is represented by generic assumptions of the ultimate strength, without test data.

When tested values are used, testing and the specification of reference mechanical strength F_r shall be carried out in accordance with the requirements in Sec.2 [3.1].

When generic assumptions are used, Table 4 applies. This table can be used as an alternative to the use of testing.

Mixing of generic assumption values and values determined by testing is subject to approval by the Society.

Table 5 Reference mechanical strength/resistance values based on strength values derived from tests in accordance with definitions in Sec.2

Laminates	Frt	Ultimate strength/strain values, tested (see Sec.2 [3.2])
Matrix dominant laminate behaviour	Frm	Interlaminar shear strength values, tested
Sandwich core	Frc	Static shear strength proved by approval certificate or qualification testing (msmv) for quasi-static applications
		Dynamic shear strength proved by approval certificate for slamming applications

Table 6 Reference values (generic) in absence of tested values as defined in Sec.2

Laminates, generic	Frg	Default ultimate strain* default values:	
		0.65%	HS Carbon, uniaxial strain
		**	HM Carbon, uniaxial strain
		1.2%	E-Glass, uniaxial strain
		0.40%	Aramid, uniaxial strain
		1.15%	HS Carbon, in-plane shear strain
		**	HM Carbon, in-plane shear strain
		2.0%	E-Glass in-plane shear strain
		0.70%	Aramid, in-plane shear strain

Table 7 Other reference values:

Stability issues	Frs	Buckling strains as determined in [6]

* = uniaxial strain with fibres aligned in load direction, in-plane shear strain values with fibres laid typically laid at +/-45° to load

** = HM carbon fibre material has to be tested.

Guidance note:

Tested reference values Fr in Table 4 may be used on laminate or ply level when the type of test specimens used and the evaluation of the test results can produce data that is representative on ply level.

All generic reference values Fr in Table 5 may be used on laminate level. The Frg specified for in-plane shear strain will ensure that the specified failure criterion, maximum strain in the fibre direction Sec.4 [2.1], is adhered to. The uniaxial generic values can also be used on ply-level.

The reference values, tested and generic, represent characteristic values with at least a 95% confidence level.

The mechanical properties of laminates depend on the properties of the constituent materials, fibres and matrix. It is however recognised that the mechanical properties of the laminates (in terms of mean strength and variability) in the finished product to a significant degree also depend on the production process and the control of the same. Test data from purpose made test laminates may not be entirely representative for the finished product. This is reflected in the specified reserve factors [7.2.2]. Sufficient control of the mechanical properties of the finished product shall be ensured by adhering to the requirements to manufacturing and production facilities given in DNVGL-RU-SHIP Pt.2 Ch.3 Sec.3 and by verification through as-built testing Sec.2 [3.2].

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

7.2.4 Sandwich core - reference mechanical strength/resistance

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 8. 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 (msmv: manufacturer’s specified minimum value) serves as a reference for application of safety factors.

7.2.5 Reserve factors

The reserve factors R describe the ratio between reference mechanical strength F_r and allowable stress/strain.

Table 8 Reserve factors

		Rule reference	*R*	
Laminates:				
uniaxial tension		[5]	3.0	
uniaxial compression		[5]	3.0	
in-plane shear		[5]	3.0	
flexural		-	3.0	
Matrix dominated behaviour:				
ILSS		-	5.0	
Stability issues:				
panel buckling		[6]	2.5	
skin wrinkling		[6]	2.0	
Sandwich cores:				
Core type	ultimate shear elongation		hull shell and watertight bulkheads	deck shell
Balsa/ Aramidhoneycomb	< 10%	[5.1.2]	2.5	2.5
Medium elongation, e.g. cross-linked PVC	< 35%	[5.1.2]	2.2	2.5
High elongation, e.g. linear PVC and SAN*	> 35%	[5.1.2]	1.7	2.5
* = carrying a type approval certificate from an IACS classification society confirming suitability for being used in slamming areas or passed an approved test using similar criteria.				

7.3 Allowable deflections

7.3.1 Deflections of panels and stiffeners/frames/girders may be larger in FRP structures than what is normally experienced in corresponding steel or aluminium structures. This may be the case also when the requirements for structural strength specified in these rules are adhered to. It is advised that such deflections may have to be considered by the yard or the designer in order to avoid unwanted effects (e.g. with respect to shaft alignment, fitting of internal structures, vibration, ensuring sufficient stiffness of decks etc.).

However, the following generic limitations apply for panels and beams. The deflections given are under a lateral uniform line load or single point load.

The deflection criteria is valid for structures solely analysed using methodologies offered directly in Sec.6, mainly following simple linear beam theory and panel theory.

The following deflection criteria are introduced mainly because:

— The deflection limit helps reducing local stress concentration, e.g. on continuous sandwich skins under a non-continuous beam.

— A deflection limit helps keeping control also over secondary deformations like transverse deflection of L-flanged beams.

The following displacements shall not be exceeded:

Table 9 Allowable deflections

	Rule reference	z_{max}/s_{eff} z_{max}/l
Deflection single skin panel	[5.1.3]	2.0%
Deflection sandwich panel	[5.1.3]	1.5%
Deflection stiffener/girder	[5.2.3]	0.5%
Deflection engine foundation	[5.2.3]	0.3%

Z_{max} = maximum deflection from [5.1.3] and [5.2.3]
S_{eff} = effective panel span from [3.2.4]
l = beam span from [4.2.2].

SECTION 7 LOCAL STRUCTURAL DESIGN

1 Design details

- The occurrence of peeling effects such as abrupt stiffness changes shall be minimised. Secondary bonding is always to be backfilled with suitably coved filler bed.
- Core chamfers of sandwich panels should not be steeper than 1/3.
- Exposed fibres and sandwich cores shall be sealed or clashed.
- Through-sandwich penetrations shall be adequately designed, e.g. by installing appropriate skin ties and/ or back-fill with structural filler.

2 Minimum laminate reinforcement weight

2.1 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 note:

Recommendations about minimum skin thickness may be obtained from DNVGL-RU-HSLC Pt.3 Ch.4 Sec.7 [2.2].

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

3 Bow impact protection

Vessels built in sandwich construction shall have the fore stem designed so that a local impact at or below the water line will not result in skin laminate peeling due to hydraulic pressure. This shall be achieved by connecting the two skin laminates.

The distance *a* Figure 1 from the stem to the location of the connection of the two skins shall not be less than:

$$a = 0.15 + \frac{1.5V^2\Delta}{10^6}\ (\mathrm{m})$$

With *V* and Δ defined in Ch.1.

The vertical extension of the collision protection shall be from the keel to a point 0.03 *L* (m) above the water line at operating speed.

Within the vertical extension of the collision protection the stem laminate shall be increased to a thickness not less than:

$$t_s = \frac{7 + (0.1V)^{1.5}}{\sqrt{\frac{\sigma_{nu}}{160}}}\ (\mathrm{mm})$$

where σ_{nu} is the ultimate tensile strength of the laminate (MPa).

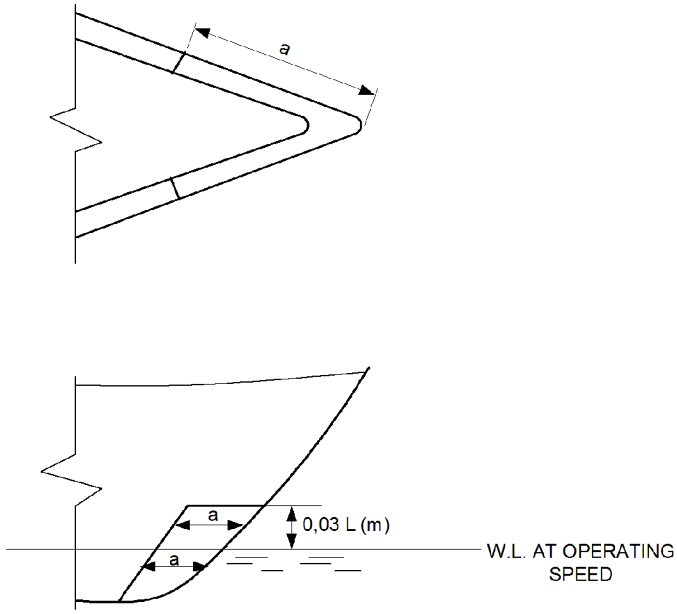

Figure 1 Collision Protection

The connection of the skin laminates can be arranged as shown in Figure 2. Other alternatives providing the same degree of protection can be accepted.

Figure 2 Laminate connection

4 Bolting

4.1 Introduction

4.1.1 In this paragraph the general requirements for strength of the following bolted connections are given:

— bolted connections for transfer of in-plane loads (shear connections)
— bolted connections for transfer of out-of-plane loads
— bolt inserts and similar attachments (not participating in the structural strength of the hull and superstructure).

The definition of in-plane and out-of-plane loads refers to the load components on each individual bolt.

Guidance note:

A bollard may be subjected to a load parallel to the laminate plane. However, due to the bending moment on the bollard (the point of attack of the load is some distance above the panel) the individual bolts securing the bollard to the panel may be subjected to an out-of-plane load, additional to the in-plane load. Such bolted connections shall be designed with respect to both in-plane and out-of-plane loads.

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

4.2 In-plane-loaded connections

4.2.1 Definitions (see Figure 3):

d = bolt diameter
e_1 = edge distance transverse to the direction of the load
e_2 = edge distance in the direction of the load
p_1 = bolt pitch transverse to the direction of the load
p_2 = bolt pitch in the direction of the load.

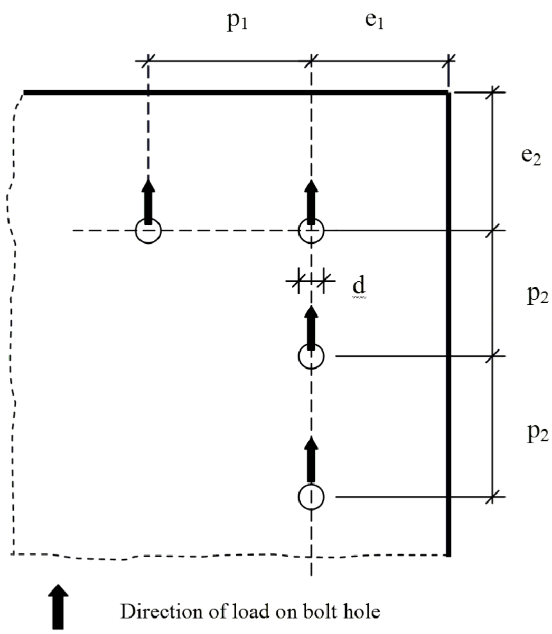

Figure 3 Definitions

4.2.2 Bolted shear connections are only accepted in laminates with reinforcement placed in at least two directions. The smallest angle between at least two reinforcement directions shall not be smaller than 75° (does not apply to pure CSM laminates). CSM plies in a combined laminate shall not be included in the calculation of the capacity of the connection.

4.2.3 The surface of the part of the bolt inside the laminate shall be smooth (plain shank bolts). No threads are allowed in this area.

4.2.4 A washer with an outer diameter not smaller than 3 *d* shall be used under the bolt head and the nut. The washer shall have adequate stiffness such that the bolt pretension is distributed under the area of the washer. Only flat-face bolts shall be used. Countersunk/tapered bolt heads are not accepted due to the risk for splitting the laminate by the wedge effect of the bolt head.

4.2.5 The bolt shall be tightened with such a force that the laminate is subjected to a nominal compressive stress under the washers, exceeding 15 MPa but not exceeding 30 MPa. The nominal stress is calculated as compressive load in the bolt divided by the surface area of the washer. Due to the creep (and thus stress relaxation) that can be expected in the laminate, bolts should be re-torqued after a period of time not shorter than two (2) weeks.

4.2.6 The pitch transverse to the direction of the load shall satisfy $p_1 \geq 5\ d$.
The pitch in the direction of the load shall satisfy $p_2 \geq 4\ d$.
The edge distance transverse to the direction of the load shall satisfy $e_1 \geq 3\ d$.
The edge distance in the direction of the load shall satisfy $e_2 \geq 4\ d$.

4.2.7 The nominal bearing stress shall satisfy the following requirement:

$$\sigma_{bear} = \frac{R_{bear}}{3\gamma}$$

where:

σ_{bear} = shear load divided by $d \cdot t$
t = thickness of structural laminate
γ = 1.0 for holes with a difference between bolt and hole diameter less than 0.1 mm
γ = 1.6 for holes with a difference between bolt and hole diameter of less than 1.0 mm.

The default values of the bearing stress capacity given in Table 1 can be used.

Table 1 Default values of the bearing stress capacity

Type of reinforcement	*Nominal bearing stress strength, R_{bear} (MPa)*
Glass, woven rowing	200 (V_f/0.33)
Glass, multiaxial laminates	250 (V_f/0.33)
Glass, CSM	75 (V_f/0.33)
Carbon, woven rowing	275 (V_f/0.50)
Carbon, multiaxial laminates	325 (V_f/0.50)
Aramid, woven rowing	Considered specially
Aramid, multiaxial laminates	Considered specially
V_f = volume fraction of reinforcement in laminates excluding CSM	

Higher bearing stress capacity can be used based on representative test results.

For hybrid laminates R_{bear} can be found by liner interpolation based on the volume fraction of the respective types of fibre.

Guidance note:

The requirements are such that it is highly probable that the failure mode will be that the bearing stress will exceed the capacity around the edge of the hole.

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

4.3 Out-of-plane loaded connections

4.3.1 A connection for out-of–plane loads shall be bolted through the panel, in sandwich panels through both skins. For attachments not participating in the structural strength of the hull and superstructure other arrangements may be accepted by the Society.

4.3.2 Washers or plates shall be provided on both sides of the panel to distribute the load from bolt heads and nuts. These washers or plates may be fabricated from metallic materials or from fibre reinforced thermosets.

Their bending stiffness shall be large enough to ensure a distribution of the load from each bolt over a sufficiently large area to prevent compressive overloading of the panel in-between the washers or plates. The compressive stress under the washer or plates shall not anywhere exceed 30% of the compressive strength of the skin and core, respectively.

4.3.3 The global effect of the out-of-plane load on the panel (in-plane bending moments and through thickness shear) shall be calculated according to recognised methods for the calculation of load effects in panels subjected to concentrated loads. The stress levels in laminates, skins and core shall not exceed the stress level accepted for hull panels in bottom exposed to slamming.

4.3.4 Other arrangements may be accepted based on test results. Such testing shall be carried out on connections with representative design on representative panels subjected to representative loads including all in-plane and out-of-plane components. The allowable loads on the connection shall not exceed the lowest strength recorded from at least three such test divided by the factor of 3.

4.4 Inserts and attachments

4.4.1 Inserts and attachments may be used for transferring in-plane and out-of-plane loads for connections not participating in the structural strength of the hull and superstructure.

4.4.2 Where adequate, the methods for design described above may be used. Where these methods are not adequate the allowable load shall be determined by testing. Such testing shall be carried out on inserts or attachments with representative design on representative panels subjected to representative loads including all in-plane and out-of-plane components. The allowable loads on the insert/attachment shall not exceed the lowest strength recorded from at least three such test divided by the factor of 3.

5 Bonded joints

5.1 Application

5.1.1 This section applies to a bonded joint defined as follows: a joint where adherents are bonded either by placing a layer of adhesive or resin material between the adherents or by producing a bond between one adherent and the second adherent as an integral part of the manufacturing of the joint or the structure, e.g. by applying laminates or laminating directly onto a metal surface, or any combination of the above. Secondary bonds in FRP constructions are not covered by this section.

5.1.2 The use of bonded joints is subject to the approval of the Society. Bonded joints are normally not accepted for transfer of the global loads on the hull or on joints, the failure of which would compromise the watertight integrity of the vessel. Deviations from this may be accepted by the Society based on special consideration.

5.1.3 Adhesives used for bonded joints shall be type approved as rigid adhesives by the Society.

5.2 Design of bonded joints

5.2.1 The function(s) of the joint shall be to transfer load by shear along the bondline. Peel loads shall be avoided.

5.2.2 The nominal shear stress over the bond surface shall not by itself be used as a characteristic of the load level in the joint. The design shall be based on line load, global load or an analysis of the shear stress taking due account of the stress concentrations in the joint.

5.2.3 The physical environment of the joint shall be specified and considered in the design. As a minimum the following factors shall be considered:

— humidity
— UV-light
— temperature
— chemicals (e.g. fuel etc.)
— welding
— fire.

Welding on adjacent structures and fire may increase the temperature at the bond. This effect shall be considered when specifying short and long term service temperature for the joint.

5.2.4 The design of bonded joints shall be based on qualification tests carried out on realistic samples, see Sec.2 [3.1]. The properties obtained in a yard may differ significantly from the properties measured on specimens tested under laboratory conditions. Causes for such differences may be different working environment, scaling effects etc. This difference shall be reflected in the design strength of the joint: the strength of the joint cannot be assumed to be as high as determined in the qualification tests.

5.2.5 For static strength verifications, a nominal allowable shear stress of:

$$t = 7\ \mathrm{N/mm}^2$$

can be used without further verification, in the case of multi-component thermosetting adhesive approved by the Society. A stress concentration arising in the structural joint is covered up to a factor of 3. This value may be assumed for bonded joints of shell with negligible level peeling forces.

5.2.6 The adherents, surface preparation and fabrication procedures shall be identical to the joint as for the samples on which the qualification tests have been carried out.

5.2.7 The joint cross section and the direction of the load transfer shall for all parameters influencing the strength and durability of the joint be identical to the joint geometry tested in the qualification tests. Alternatively, a change in any of these parameters may be accepted if they do not lead to a reduction of the strength or durability of the joint.

Special attention shall be given to the length of the overlap, the stiffness of the adherents and the out-of plane forces in the joint. The length of the overlap shall not be smaller than on the tested joint. The thickness of the adherents shall not be smaller than used in the qualification tests.

CHANGES – HISTORIC

October 2016 edition

This document supersedes the December 2015 edition of DNVGL-RU-YACHT Pt.3 Ch.5.

Amendments July 2017

Editorial changes have been made.

Main changes October 2016, entering into force as from date of publication

• Sec.6 Scantlings

— Sec.6 [5.1.1]: Stiffness matrix terms have been corrected. There was a mistake in the assumption, that coupling terms of stiffness matrix could be neglected, corrected by including coupling terms and a note.

December 2015 edition

This is a new document.

The rules enter into force 1 July 2016.

About DNV GL
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