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PROPELLER IN COMPOSITE MATERIALS

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GUIDANCE NOTE

BUREAU VERITAS

BUREAU VERITAS
RULES, RULE NOTES AND GUIDANCE NOTES

NI663 DT R01 March 2023 takes precedence over previous revision.

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These rules are provided within the scope of the Bureau Veritas Marine & Offshore General Conditions, enclosed at the end of Part A of NR467, Rules for the Classification of Steel Ships. The current version of these General Conditions is available at the Bureau Veritas Marine & Offshore website.

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NI663

PROPELLER IN COMPOSITE MATERIALS

March 2023

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Section 1 General

1 Application

1.1 General

1.1.1 The present Guidance Note defines the procedures and requirements for certification, design, construction, installation, test, trials and surveys of propellers, made of composite material, to be fitted on board ships classed with the Society.

Note 1: For propellers made of metallic materials, reference is made to:

- Pt C, Ch 1 Sec 8 or Pt C, Ch 1, Sec 15 of NR467 Rules for the Classification of Steel Ships
- Ch 2, Sec 2 of NR566 Hull Arrangement, Stability and Systems for Ships less than 500 GT.

1.1.2 This Guidance Note is mainly dedicated to composite propellers intended for propulsion.

Other propellers and impellers in rotating or bow and stern thrusters (in a revolving nozzle or transverse thruster, azimuth thruster and water-jet impeller) may be considered on a case-by-case basis by the Society.

1.1.3 Products and materials intended to be fitted on board ships classed by the Society are subject to compliance with the requirements of NR320 Certification scheme of materials and equipment for the classification of marine units.

For the purpose of this Guidance Note:

- the certification scheme requirements for propellers made of composite materials are specified in Sec 2
- the general procedures of the raw material certification are specified in Sec 3
- work's recognition scheme requirements are specified in Sec 4
- testing procedures are specified in Sec 5.

1.1.4 Equipment and systems to be installed on board ships classed by the Society are to comply with:

- the relevant rules for materials and equipment covered by the class
- the specific requirements for design, manufacture, testing and certification given in the relevant Society rules for classification
- the general principles of classification given in Part A of NR467 Rules for the Classification of Steel Ships.

For the purpose of this Guidance Note:

- the design assessment requirements for propeller made of composite materials are specified in Sec 6.
- Arrangement, installation and sea trials requirements are specified in Sec 7.
- The principles of in-service surveys are specified in Sec 8.

2 Definitions

2.1 Propulsion propellers

2.1.1 Solid propeller

A solid propeller is a propeller (including hub and blades) made in one piece.

2.1.2 Built up propeller

A built-up propeller is a propeller made in more than one piece. In general, built up propellers have the blades made separately and fixed to the hub by a connection system.

2.1.3 Controllable pitch propeller

Controllable pitch propellers are built-up propellers which include in the hub a mechanism to rotate the blades in order to have the possibility of controlling the propeller pitch in different service conditions.

2.1.4 Nozzle

A nozzle is a circular structural casing enclosing the propeller.

2.1.5 Ducted propeller

A ducted propeller is a propeller installed in a nozzle.

2.2 Thrusters

2.2.1 Transverse thruster

A transverse thruster is an athwartship thruster developing a thrust in a transverse direction for manoeuvring purposes.

2.2.2 Azimuth thruster

An azimuth thruster is a thruster which has the capability to rotate through 360° in order to develop thrust in any direction.

2.2.3 Water-jet

A water-jet is an equipment constituted by a tubular casing (or duct) enclosing an impeller. The shape of the casing is such as to enable the impeller to produce a water-jet of such intensity as to give a positive thrust. Water-jets may have means for deviating the jet of water in order to provide a steering function.

3 Documents to be submitted

3.1 Documents to be submitted for classification purpose

3.1.1 Solid propellers

Documents to be submitted for solid composite propellers intended for propulsion are defined in Tab 1.

All listed plans are to be constructional plans complete with all dimensions.

3.1.2 Built-up propellers

The following document are to be submitted for built-up composite propellers intended for propulsion:

- documents defined in [3.1.1], as applicable
- additional documents defined in Tab 2.

3.1.3 Other propellers (controllable pitch propellers, ducted propellers and thrusters)

The following document are to be submitted for controllable propeller, ducted propeller, transverse propeller, azimut thruster or waterjet:

- documents defined in [3.1.1], as applicable
- additional documents requested by the Society on a case-by-case basis.

Table 1 : Documents to be submitted for solid propellers

No.	A/I **(1)**	ITEM
1	A	Sectional assembly
2	A	Blade and hub details
3	I	Rating (power, rpm, etc.)
4	A	Data and procedures for fitting propeller to the shaft
5	A	Test reports
6	I	Calculation reports
7	I	Material Type Approval Certificates
(1) A = to be submitted for approval I = to be submitted for information		

Table 2 : Additional documents to be submitted for built-up propellers

No.	A/I **(1)**	ITEM
8	A	Blade bolts and pre-tensioning procedures
(1) A = to be submitted for approval I = to be submitted for information		

3.2 Other documents to be submitted for materials

3.2.1 For parts of the propeller manufactured in composite materials, the following informations are to be submitted:

- list of main raw materials used to manufacture the composite propeller (resin systems, fibre types, type of reinforcement fabrics, foam cores) (see Sec 3)
- laminate composition (see App 2).
- lamination process (see Sec 4, [2.3])

3.2.2 For parts of propeller manufactured in metallic materials (hub, studs), the materials grades and properties are to be submitted to the Society considering the requirements of NR216 Rules on Materials and Welding.

4 Reference documents

4.1 Bureau Veritas Rules

4.1.1 The following list of documents is given as reference:

- NR216 Rules on materials and welding for the classification of marine units
- NR320 Certification scheme of materials and equipment for the classification of marine units
- NR467 Rules for the classification of steel ships
- NR546 Hull in composite materials, material approval, design principles, construction and survey.

Section 2 Certification Scheme

1 Process of certification

1.1 General

1.1.1 The certification comprises Society's interventions during following phases:

- design phase
- production phase.

1.1.2 Design phase

The purpose of the Society's interventions during the design phase is to examine whether the propeller is designed and documented according to the present Guidance Note.

As a rule, the design phase involves the following steps:

- raw materials type approval
- design assessment of propeller
- sample tests, prototype tests, full scale blade tests and sea trials.

Upon satisfactory completion of the design phase assessment, a type approval certificate is issued by the Society to the manufacturer for the type of propeller considered.

1.1.3 Production phase

The principles and conditions of product certification are defined in NR320 Certification scheme of materials equipment for the classification of marine units.

As defined in NR320, propeller blade made from composite materials may be considered as I_{BV} product, having to be certified individually or per batch.

2 Raw material type approval

2.1 General

2.1.1 As a rule, the main raw materials to be submitted to a certification program are:

- resin systems
- reinforcement fabrics
- core materials for sandwich laminates
- adhesives.

The general procedure of the raw material certification is specified in Sec 3.

3 Design assessment of propeller

3.1 General

3.1.1 The purpose of the design assessment, based on the drawings and technical specifications listed in Sec 1, [3] is to examine whether the propeller is designed in compliance with requirements defined in the present Guidance Note.

The specific requirements for design assessment of propeller are defined in Sec 6.

4 Sample tests, prototype tests, full scale blade tests

4.1 Sample tests on laminate

4.1.1 General

Mechanical and physico-chemical tests are to be performed by the propeller Manufacturer on test panels representative of the scantling and the manufacturing process used for the propeller manufacturing.

The results of the mechanical tests are to be compared with the theoretical properties of the propeller laminate determined on the basis of the requirements of the present Guidance Note and considered for the structure design assessment as required in Sec 6.

Testing reports are to be submitted by the Manufacturer to the Society. Attendance to tests may be required by the Society.

The sample tests procedures on laminates are defined in Sec 5, [2].

4.2 Prototype tests

4.2.1 As a general rules, a full scale static load test is to be carried out by the Manufacturer on one blade or a part of the blade to demonstrate that the prototype under test displays the behaviour provided by the design.

Testing reports are to be submitted to the Society for approval. Attendance to tests may be required by the Society.

The prototype tests procedures are defined in Sec 5, [2].

4.3 Full scale blade tests

4.3.1 The full scale blade tests procedures are defined in Sec 5, [3].

Section 3 Composite Material Certification

1 Raw materials

1.1 General

1.1.1 The mechanical characteristics of laminates used for composite structure depend on raw materials' characteristics.

The raw materials considered are of four main types: resin systems, reinforcements, core materials and adhesives. Other raw materials used for propeller may be considered on a case by case basis.

General informations about the main raw materials are given in NR546 Hull in Composite Materials.

2 Certification of raw materials

2.1 General

2.1.1 Application

The purpose of this Section is to give the procedure to be followed by the Manufacturer for the certification of raw materials used in the manufacturing of propeller made from composite materials within the scope of classification and/or certification.

Procedures for raw materials not explicitly included in this Section are subject to special consideration by the Society.

2.1.2 Certification program

As a general rule, raw materials manufactured in series correspond to H_{BV} product according to NR320 Certification scheme of materials equipment for the classification of marine units.

The type approval process of raw materials requests the two following successive phases:

- Design type approval: to review the technical documentation and mechanical characteristics proposed by the supplier in compliance with the rule requirements (see [2.2])
- Work's recognition: to assess the compliance of the raw materials manufactured in series with the design type approval (see [2.3]).

Upon satisfactory completion of the two phases, a type approval certificate and a recognition certificate are issued by the Society under conditions defined in NR320 Certification Scheme of Materials & Equipment.

A manufacturer's document stating the results of tests performed and/or stating compliance with the approved type is to be supplied by the manufacturer together with the product.

The Manufacturer is fully responsible for the quality of the finished raw materials and is to ensure compliance with the specified requirements.

2.2 Type approval of raw materials

2.2.1 Approval test program

The review of the technical documentation and the type test program are to be carried out as defined in NR320 Certification Scheme of Materials & Equipment.

The test program, drawn up by the supplier is to be submitted to the Society, as well as the minimum required mechanical test results as defined in Tab 1.

Upon Society satisfaction, some tests may be dropped from this list, and other additional tests may be requested, depending on the particular use, or experience acquired, with the materials under approval test program.

Technical reports, issued in the forms stipulated in standards indicated in Tab 1, are to be submitted to the Society.

2.3 Work's recognition

2.3.1 The general requirements for the work's recognition schemes are defined in Sec 4.

Table 1 : Approval test program

<table>
<tr><th>Raw material</th><th colspan="2">Property / Characteristics</th><th>Required value</th><th>Recommended test method/ Required value</th></tr>
<tr><td rowspan="2">Polyester gel coat (cured) **(1)**</td><td>Tensile:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td>• ≥ 3000
• ≥ 2,5</td><td>ISO 527 or equivalent **(2)**</td></tr>
<tr><td colspan="2">Water absorption (mg) over 28 days</td><td>≤ 80</td><td>ISO 62 Method 1 or equivalent **(3)**</td></tr>
<tr><td rowspan="3">Resin systems **(1)**</td><td colspan="2">Density</td><td>Manufacturer nominal value ± 1%</td><td>ISO 1183 or equivalent</td></tr>
<tr><td>Tensile:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td>≥ 85% of the values given in NR546</td><td>ISO 527 or equivalent **(2)**</td></tr>
<tr><td colspan="2">Glass transition temperature</td><td>≥ to Manufacturer value</td><td>ISO 11357 or equivalent</td></tr>
<tr><td rowspan="3">Adhesive **(4) (5)**</td><td>Tensile:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td rowspan="2">Manufacturer nominal value ± 10%</td><td>ISO 527
ASTM D 638</td></tr>
<tr><td>Shear:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td>ISO 11003-2
ASTM D 3983
NF EN 14869-2</td></tr>
<tr><td colspan="2">Glass transition temperature</td><td>≥ to Manufacturer value</td><td>ISO 11357 or equivalent</td></tr>
<tr><td>Yarn</td><td colspan="2">Weight per unit of length (tex)</td><td rowspan="2">Manufacturer nominal value ± 10%</td><td>ISO 1889 or equivalent **(6)**</td></tr>
<tr><td rowspan="2">Chopped strand mat</td><td colspan="2">Weight per unit of area (g/m²)</td><td>ISO 3374 or equivalent **(7)**</td></tr>
<tr><td>Tensile tests on laminate:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td>See NR546</td><td>ISO 3268 or equivalent</td></tr>
<tr><td rowspan="2">Woven roving and unidirectional</td><td colspan="2">Weight per unit of area (g/m²)</td><td>Manufacturer’s nominal value ± 10%</td><td>ISO 4605 or equivalent **(8)**</td></tr>
<tr><td>Tensile tests on laminate:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td>See NR546</td><td>ISO 3268 or equivalent **(9)**</td></tr>
<tr><td rowspan="4">Pre-preg</td><td colspan="2">Percentage of reinforcements in mass (%)</td><td rowspan="2">Manufacturer’s nominal value ± 5%</td><td>ISO 1172 or equivalent **(8)**</td></tr>
<tr><td colspan="2">Weight per unit of area (g/m²)</td><td>ISO 10352 or equivalent **(8)**</td></tr>
<tr><td>Tensile tests on laminate:</td><td>• modulus (N/mm²)
• elongation at break (%)</td><td>See NR546</td><td>ISO 3268 or equivalent **(9)**</td></tr>
<tr><td colspan="2">Determination of glass transition temperature</td><td>Manufacturer’s nominal value ± 5%</td><td>ISO 11357-2 or equivalent **(1)**</td></tr>
<tr><td rowspan="5">Foam for sandwich (for core structural use) **(11)**</td><td colspan="2">Density (kg/m³)</td><td rowspan="2">Manufacturer’s nominal value ± 5%</td><td>ISO 845 or equivalent **(10)**</td></tr>
<tr><td colspan="2">Tensile modulus (N/mm²)</td><td>ISO 1926 or equivalent</td></tr>
<tr><td>Shear:</td><td>• modulus (N/mm²)
• ultimate strength (N/mm²)</td><td>≥ 85% of the values given in NR546</td><td>ISO 1922 or equivalent</td></tr>
<tr><td colspan="2">Water absorption (% in volume for 7 days)</td><td>≤ 2,5%</td><td>ISO 2896 or equivalent **(12)**</td></tr>
<tr><td>Styrene resistance (when applicable):</td><td>• dimensional control
• mass control</td><td>≤ 2%</td><td>ISO 175 or equivalent **(10)**</td></tr>
</table>

(1) Curing process of the samples to be specified by the Manufacturer.
(2) Length of sample: 150 mm.
(3) Distilled water at 23° C. Circular sample of 50 mm diameter and 3 mm thickness.
(4) Curing process and material of sample pieces to be specified by the Manufacturer.
(5) Tests may be requested at different temperature range (see Sec 4, [5.2.3]).
(6) Three samples of 1 m length.
(7) Six samples 300 mm x 300 mm.
(8) Three samples 300 mm x 300 mm.
(9) Tensile tests are to be carried out in the two main directions of reinforcement. To test fabrics other than pre-preg, samples are to be made with a resin of an approved type. As a rule, samples are to be made with at least three layers of the fabric to be approved. Measurements of percentage of reinforcement in mass are to be carried out on samples submitted to tensile test.
(10) Three samples 100 mm x 100 mm x plate thickness.
(11) It may be requested, for foam used in sandwich panel cured with a heat process, that test foam samples be subjected to the same heat process before the test.
(12) Three samples 150 mm x 150 mm x thickness (minimum volume = 500 cm³ per sample).

Section 4 Work's Recognition Scheme

1 General

1.1 Application

1.1.1 The principles are defined in NR320 Certification scheme of materials equipment for the classification of marine units.

2 Recognition process

2.1 General procedure

2.1.1 The following procedures are to be submitted by the manufacturer to the Society:

- Traceability
  - procedure to ensure traceability of raw materials and equipment covered by the Society's Rules (from the purchase order to the installation or placing on ship)
  - data to ensure traceability of the production means (describing different steps during production, such as inspection or recording)
  - handing of non-conformities (from the reception of materials or equipment to the end of the construction)
  - handling of client complaints and returns to after-sales department.
- Construction
  - identification of laminating site on lay-out plan
  - laminating method (e.g. hand or spray lay-up, pre-pregs, infusion, etc.)
  - average time elapsing between applications of layers
  - hygrometry and temperature monitoring (minima and maxima of temperature and hygrometry)
  - location of hygrometer and thermometer in laminating unit.
- Assembly operations
  - types of assembly (e.g. glue-assembly, bolting connection)
  - physico-chemical preparations of parts for assembly
  - areas of completion of such preparations (where such operations generate large amounts of dust, details of the precautions taken to limit the effects on assembly work or other operations performed nearby, such as gel-coating or laminating, are to be specified)
  - procedure to ensure that the propeller is built in accordance with the approved prototype
  - builder's inspection process and handling of defects
  - procedure to ensure that the remedial measures concerning the defects and deficiencies noticed by the Surveyor of the Society during the survey are taken into account.

2.2 Materials

2.2.1 The following details about raw materials used in the propeller manufacturing (gel coats, laminating and bonding resins, reinforcements, core materials and adhesives) are to be submitted by the manufacturer to the Society:

- list of raw materials used (gel-coats, resins, catalysts/ accelerators and/or hardeners, reinforcements, core materials, adhesives, etc.) with their reference and the supplier's identification
- references of existing raw material type approval certificates
- raw material data sheets containing, in particular, the supplier's recommendations on storage and use.

2.2.2 Storage conditions

The storage conditions of raw materials are to be in accordance with the manufacturer's recommendations.

All the raw materials are to be identifiable in the storage site (product and batch references, type of approval certificates).

The builder is to provide an inspection to ensure that the incoming raw materials are in accordance with the purchase batches and that defective materials have been rejected.

The following details about storage conditions are to be submitted by the manufacturer to the Society:

- identification of storage site on yard lay-out plan (specifying all the separated storage sites and those equipped with ventilation and/or air conditioning system)

- storage conditions:
  - summer maximum temperature and relative humidity
  - winter minimum temperature and relative humidity
- temperature and hygrometry monitoring (i.e. recording)
- keeping and presence of logbook (e.g. consignment number, dates) for inventory control.

2.2.3 Preparation of raw materials

The following details about raw material preparation are to be submitted by the manufacturer to the Society:

- resins and gel-coats
  - identification of preparation unit on lay-out plan
  - manufacturer's specifications and recommendations
  - resin blend in method and preparation procedure
  - accompanying data sheets.
- reinforcement fabrics and core materials
  - identification of preparation area on lay-out plan
  - preparation procedure
  - accompanying data sheets.
- gel-coating unit
  - locations with details of means of separation from other workshops
  - equipment in gel-coating units: air conditioning, ventilation, dust extraction
  - hygrometry and temperature monitoring: number of hygrometers/thermometers, positioning, recording and height about ground level
  - laying procedure
  - moulds: type of mould, storage of moulds, preparation procedure (e.g. heating, cleaning, waxing)
  - accompanying data sheets.

2.2.4 Traceability of raw materials

The following information on raw material traceability are to be registered by the manufacturer during construction:

- for gel-coats, resins and adhesives:
  - amount of the various components necessary to prepare the resin systems in relation to the temperature in the laminating unit
  - batch reference, date and time of laminating.
- for reinforcement fabrics:
  - precautions taken to prevent condensation caused by the temperature difference
  - identification of reinforcement fabrics and location in the hull
  - batch reference, date and time of laminating.
- for core materials:
  - precautions taken to prevent condensation, to avoid gather dust and to reduce the amount of gazing
  - identification of core materials and adhesives used for laminating
  - batch reference, date and time of laminating.

2.3 Laminating process

2.3.1 The following information on the different stages of the laminating process are to be registered by the manufacturer during construction:

- date and time of the operation
- temperature and hygrometry during the operation
- reference of raw materials used
- reference of laminating drawings used
- directions of reinforcement fabrics
- preparation of the laminated zone intended for subsequent re-laminating or gluing.
- other process (connections between blade and hub).

2.4 Testing

2.4.1 The non destructive testing and the result acceptance criteria are to be defined by the manufacturer.

The non destructive testing processes may be:

- ultra-sonic testing
- spectroscopy
- thermography
- radiography.

3 Certification

3.1 General

3.1.1 The general conditions to issue the recognition certificate are defined in NR320 Certification scheme of materials equipment for the classification of marine units and are reminded in [3.2] for information only.

3.2 Recognition certificate

3.2.1 Upon satisfactory completion of the process, a recognition certificate is issued by the Society to the manufacturer.

The recognition certificate contains the categories and types of products considered for the recognition process.

Section 5 Testing Procedures

1 General

1.1 Definitions

1.1.1 Sample

A sample is a specimen representative of the laminate in the current section of the blade. In case of large variation of the scantling along the blade length or chord, or in case of using several kind of materials, more samples may be required by the Society.

1.1.2 Prototype

A prototype is a full scale representative of the blade. The scantling and the hub connection are to be similar to the blade. The shape may differ to the original one and is to be accepted by the Society before testing.

1.2 Application

1.2.1 The testing procedures consist of the completion of the following successive stages of testing:

- mechanical sample tests on laminate: these tests aim to confirm the mechanical properties of basic samples, representative to the propeller scantling and manufacturing process, in relation with the theoretical characteristics taken into account for the design assessment
- prototype tests: these tests aim to confirm the behaviour of a propeller blade and the hub/blade connection, under loads taken into account for the design assessment
- full scale blade controls: these tests aim to control main characteristics of the blade after fabrication
- sea trials: these trials aim to examine the complete propeller installation and to carry out operating tests.

1.2.2 For each stage of testing, a testing plan specifying the test procedures and the acceptance criteria is to be submitted to the Society by the Manufacturer for approval.

2 Mechanical sample tests

2.1 General

2.1.1 This Article specifies the mechanical and physico-chemical tests to be performed on sample tests.

To be representative of the propeller to certify, the sample tests are to be:

- manufactured from the same raw materials as the propeller
- manufactured by an equivalent manufacturing process as the propeller and in the same environment
- of an equivalent laminate composition as the scantling taken into account for the design assessment. The laminate composition of the sample tests is to be submitted to the Society for approval before tests.

2.1.2 Tests comprise destructive mechanical and physico-chemical tests.

Tests may be carried out in two perpendicular directions of the samples.

As a rule, the following tests are to be performed:

- measurement of density
- reinforcement content in weight
- tensile tests
- bending tests
- interlaminar shear tests
- immersion test as per ISO 62.

2.1.3 Unless otherwise agreed, the manufacturer is to submit to the Society the type test program detailing the tests to be carried out, the test standards considered, the time schedule and the location of the testing facilities.

The tests are to be carried out in the presence of the Surveyor, unless otherwise agreed.

Upon completion of the testing, the manufacturer is to submit to the Society for approval a test report containing the tests results.

The Society may take into account on a case by case basis tests performed by the manufacturer before the certification.

2.1.4 Other tests

The following tests may be required by the Society on a case by case basis:

- Ageing: Blade is to be protected against water absorption and durability duly justified. The Society may require some ageing tests on a case by case basis.

- Fatigue: Fatigue resistance is to be evaluated on the basis of stress to number of cycles established by tests. Fatigue tests consist in performing cycling tests on representative laminates sample to determine the S/N curve. The ratio of loading is to be considered on a conservative approach and agreed with the Society.

  S/N curve obtained by tests is to be used for design assessment defined in Sec 6.
- Impact: Resistance of leading edge and trailing edge is to be demonstrated by impact tests. Indenter shape and kinetic energy are to be duly justified.

2.2 Prototype tests

2.2.1 Static tests

Prototype tests should be carried out on a blade or on a piece as much as possible representative of the type of propeller concerned. The objective of these tests are also to confirm numerical simulations by an experimental approach. The comparison with a Finite Element Model is mandatory by measuring stresses and displacement in two locations, 0,25.R and 0,6.R (where R is the blade radius) considering a load representative of 1,25 times induced bending moment and shear force (generated by maximum thrust and torque in continuous regime).

As far as possible, these type of tests must be used for the validation of the blade connection to the shaft line hub. Indeed, the connection to the hub is a critical point for the propeller and the numerical approach may not be sufficient for stresses and strains assessment.

2.2.2 Fatigue tests

The Society may require to perform fatigue tests on prototype to justify design and hub connection. The ratio of loading is to be considered on a conservative approach and agreed with class. Test procedure is to be submitted to the Society before testing.

3 Full scale blade test

3.1 General

3.1.1 The full scale blade tests consist in the following control of each blade:
- dimensions
- weight
- centre of gravity
- stiffness (modal analysis/eigenvalue).

In addition of these controls, some non-destructive tests (NDT) may be carried out in order to verify the quality of the blade all along the production process.

Note 1: A list of possible NDT methods is available in Guidance Note NI 613 Adhesive joints and repairs.

For each blades, records of values shall be kept in order to be used as reference for in service inspection.

4 Balancing

4.1 General

4.1.1 Finished propellers are to be statically balanced in accordance with the specified ISO 484 tolerance class. However, for built-up and controllable pitch propellers, the required static balancing of the complete propeller may be replaced by an individual check of blade weight and gravity centre position and stiffness as per mentioned in Article [3].

Section 6 Design Assessment of Propeller

1 General

1.1 Assessment methods

1.1.1 The present Guidance Note is based on two assessment methods:

- an analytical method for basic design
- a numerical method for final design.

1.1.2 Basic design

An analytical method is described in [4.1] which permits to assess a pre-scantling of propeller blade on the basis of the propeller performance characteristics.

1.1.3 Final design

The final design is to be assessed with a method based on hydrodynamic calculations and finite element analysis as defined in [4.2].

2 Scantling criteria

2.1 General

2.1.1 The structure scantling criteria of propeller blade made of composite materials, for thick blade section laminates, are based on the calculation of actual safety factors, equal to the ratio between:

- the theoretical breaking stresses of each individual layers of laminates defined in App 1
- the actual applied stresses induced by external loads calculated according to Article [4].

The actual safety factors are to be greater than the minimum rule safety factors defined in [2.2].

Note 1: Breaking stresses directly deduced from mechanical tests may be taken over from theoretical breaking stresses defined in App 1 if mechanical test results are noticeably different from expected values.

Those structural scantling criteria might be adapted on case-by-case basis depending on blade design. For hollow profile propeller blade with thin skins, buckling of laminate is also to be checked, by tests or by simulations, with adapted associated safety factors defined on a case-by-case basis.

2.1.2 Types of stresses considered

The different types of stresses considered to estimate the actual safety factors are:

a) For main stresses analysis in each individual layer ("ply by ply" analysis):
   - main tensile or compressive stresses σ_1 in the longitudinal direction of the fibre, mostly located in:
     - 0° direction of unidirectional tape
     - 0° and 90° directions of woven roving when the set of fibres are interweaved
   - main tensile or compressive stresses σ_2 in the perpendicular direction of the fibre, mostly located in:
     - 90° direction of unidirectional tape or combined fabrics when the set of fibres are stitched together without criss-crossing of fibre
   - main shear stresses parallel to the fibre located in the plane of the individual layer (τ_{12}) and/or between each individual layer (τ_{IL1} and τ_{IL2}, also designated as inter-laminar shear stresses).

b) For combined stress analysis in each individual layer ("ply by ply" analysis):
   - combined stresses calculated according to the Hoffman criterion.

2.2 Rules safety factors for composite parts

2.2.1 General

The minimum rule safety factors are defined in relation with partial safety factors α, C_V, C_F, C_R, C_i, C_{CS} defined as follow:

α : Rule partial safety factor taking into account the accuracy of calculation methods used for the design check

C_V : Rule partial safety factor taking into account the ageing effect on the laminates

C_F : Rule partial safety factor taking into account the fabrication process and the reproducibility of the fabrication, directly linked to the mechanical characteristics of the laminates

C_R : Rule partial safety factor taking into account the type and the direction of main stresses applied to the fibres of the reinforcement fabric of the laminates

C_{CS} : Rule partial safety factor for combined stresses in the individual layers of the laminates

C_i : Rule partial safety factor taking into account the type of loads.

2.2.2 Main stresses analysis in the individual layers

The minimum rule safety factor SF in each layer is to fulfil the following condition:

$SF \geq \alpha \cdot C_V \cdot C_F \cdot C_R \cdot C_i$

2.2.3 Combined stresses analysis in individual layers

The minimum rule safety factor SF_{CS}, applicable to the combined stresses in each layer, is to fulfil the following condition:

$SF_{CS} > \Sigma\Phi_{CSiapp}$

where:

$SF_{CS} = \alpha \cdot C_{CS} \cdot C_V \cdot C_F \cdot C_i$

SF_{CSiapp} : Equal to the positive value of:

$$SF_{CSiapp} = \frac{-b \pm \sqrt{b^2 + 4a}}{2a}$$

with:

$$a = \frac{\sigma_1^{\ 2}}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\sigma_2^{\ 2}}{|\sigma_{brc2}\sigma_{brc2}|} - \frac{\sigma_1\sigma_2}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\tau_{12}^{\ 2}}{\tau_{br12}^{\ 2}}$$

$$b = \frac{\sigma_1(|\sigma_{brc1}| - |\sigma_{brt1}|)}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\sigma_2(|\sigma_{brc2}| - |\sigma_{brt2}|)}{|\sigma_{brc2}\sigma_{brt2}|}$$

σ_i, τ_{12} : Actual stresses, in N/mm², in the considered local ply axis induced by the loading case considered and calculated as defined in App 2

σ_{bri}, τ_{br12}: Ply theoretical breaking stresses, in N/mm², in the local ply axis, as defined in App 1.

Note 1: The combined criterion SF_{CSiapp} is obtained from the following equation:

$SF_{CSiapp}^{\ 2} \cdot F_{ij} \cdot \sigma_i \cdot \sigma_j + SF_{CSiapp} \cdot F_i \cdot \sigma_i > 1$

2.2.4 Partial safety factors for composite parts

As a general rules, the minimum values of partial safety factors are to be taken equal to:

a) Type of calculation factor α:

α takes into account the accuracy of calculation method used in the design check and is generally taken equal to:

- $\alpha = 1,6$ in the case of basic design
- $\alpha = 1,1$ in the case of final design

b) Ageing effect factor C_V

C_V takes into account the ageing effect of the composites and is generally taken equal to:

- $C_V = 1,2$ for monolithic laminates (or for face-skins laminates of sandwich)
- $C_V = 1,1$ for sandwich core materials

c) Fabrication process factor C_F

C_F takes into account the fabrication process and the reproducibility of the fabrication and is generally taken equal to:

- $C_F = 1,10$ in case of a prepreg process
- $C_F = 1,15$ in case of infusion and vacuum process
- $C_F = 1,25$ in case of a hand lay-up process
- $C_F = 1,00$ for the core materials of sandwich composite

d) Type of stress factor C_R and C_{CS}

C_R takes into account the type of stress in the fibres of the reinforcement fabrics and the cores and is generally taken equal to:

1) For fibres of the reinforcement fabrics:

- for tensile or compressive stress parallel to the continuous fibre of the reinforcement fabric:
  - $C_R = 2,1$ for unidirectional tape, bi-bias, three-unidirectional fabric
  - $C_R = 2,4$ for woven roving
- for tensile or compressive stress perpendicular to the continuous fibre of the reinforcement fabric:
  - $C_R = 1,25$ for unidirectional tape, bi-bias, three-unidirectional fabric
- for shear stress parallel to the fibre in the elementary layer and for interlaminar shear stress in the laminate:
  - $C_R = 1,6$ for unidirectional tape, bi-bias, three-unidirectional fabric
  - $C_R = 1,8$ for woven roving

2) For core materials:
   - for tensile or compressive stress for cores:
     - in the general case:
       C_R = 2,1 for tensile or compressive stress
     - for balsa:
       C_R = 2,1 for tensile or compressive stress parallel to the wood grain
       C_R = 1,2 for tensile or compressive stress perpendicular to the wood grain
   - for shear stress, whatever the type of core material:
     C_R = 2,5

C_{CS} takes into account the type of stress in the fibres of the reinforcement fabrics for the combined stresses calculation and is generally taken equal to:

C_{CS} = 1,7 for unidirectional tape, bi-biais, three-unidirectional fabric

C_{CS} = 2,1 for other types of layers

e) Type of load factor C_i

C_i takes into account the type of loads and is generally taken equal to:

C_i = 2,2 for static loads without fatigue considerations.

2.3 Safety factors for blade hub connections

2.3.1 Composite part

In way of the connection system made with systems radial to the shaft (bolts or keys), contact stresses in plane, if any, induced by contact forces are to be checked in each layer of laminate ensuring propeller connection system. Those contact forces might be generated by blade thrust, blade torque. Scantling criteria are to be as defined as in [2.2.2] and [2.2.3] where SF and SF_{CS} are to be reduced to 55%.

Any other arrangement may be considered on a case-by-case basis.

2.3.2 Metallic part

For Blade-hub connection system with bolts radially mounted to the shaft:

- the Von Mises combined stress of each bolts is to be less than 0.5 R_{eh} where R_{eh} is the minimum yield strength of the bolts, in N/mm²
- a particular attention is to be paid on the transmission of forces in a reduced section due to number of thread for bolts.

Requirements for the scantling of metallic propeller hub are given in NR467 Pt C, Ch 1, Sec 8.

For propeller shaft keys and keyways scantlings, refer to NR467, Pt C, Ch 1, Sec 7, [2.5.5].

2.4 Safety factors for fatigue

2.4.1 General

When deemed necessary by the Society, fatigue analysis of the prototype and its connections with hubs, based on recognised method, is to be submitted for examination or a full scale testing may be required.

2.4.2 Fatigue for composite components

As a rule, when actual safety coefficients calculated as defined in [2.1.1] for static loads, taking into account hydrodynamic loads, are greater than the minimum values given in [2.2.2] and [2.2.3], fatigue analysis as per [6] is normally not required.

2.4.3 Fatigue for metallic components

Fatigue for bolts and bolts assembly shall be checked according to NI 611, Sec 8, [2.2].

Note 1: NI611 Guidelines for fatigue assessment of steel ships and offshore units

3 Loads

3.1 Propeller loads

3.1.1 From geometrical informations of the propeller, propeller performance characteristics are to be calculated as follow:

- torque coefficient (non dimensional):

$$K_Q = 0{,}1142 \cdot \left(\frac{P_D}{n^3 D^5}\right)$$

- propeller torque, in N.m:

$$Q = \rho \cdot K_Q \cdot n^2 \cdot D^5$$

- thrust coefficient (non dimensional):

$$K_T = \frac{2 \cdot \pi \cdot n_0 \cdot K_Q}{\frac{V}{n \cdot D}}$$

- propeller thrust, in N:

$$T = \rho \cdot n^2 \cdot D^4 \cdot K_T$$

- advance coefficient (non dimensional):

$$J = \frac{V}{n \cdot D}$$

where:

P_D : Delivered power, in hp

D : Propeller diameter, in m

ρ : Density of water, in kg/m^3

n : Propeller rotational speed, in rps

V : Vessel speed, in m/s

n_0 : Propeller efficiency.

3.2 Loads to be considered for analytical calculation method - Basic design

3.2.1 Blade loads

From propeller performance characteristics determined in accordance with [3.1], forces and moment per blade are to be calculated as follow:

- blade thrust, in N:

$$F_T = \frac{T}{z}$$

F_T application point is considered at 0,7 blade radius, according to Fig 1

- blade torque, in N.m:

$$M_Q = \frac{Q}{z}$$

- blade torque force, in N:

$$F_Q = \frac{M_Q}{0,66^D/2}$$

F_Q application point is considered at 0,66 blade radius, according to Fig 1

- centrifugal force, in N:

$$F_C = 2 \cdot \pi^2 \cdot m \cdot x_C \cdot D \cdot n^2$$

where:

z : Number of blades

x_C : Ratio equal to the blade centroid radial position divided by the blade radius

m : Blade mass, in kg.

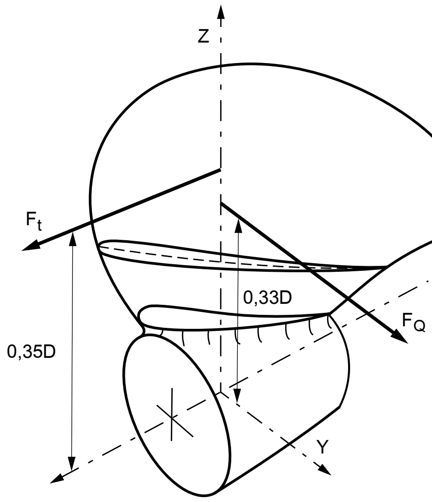
When the blade mass is unknown, m may be taken equal to:

$$m = 0,75 \cdot e_p \cdot \frac{\pi\left(\frac{D}{2}\right)^2}{z} \cdot \rho_m \cdot 10^{-3}$$

e_p : Mean radial thickness above considered section, in mm

ρ_m : Mean density of the blade, in kg/m^3, taking into account all constitutive elements of the blade.

Figure 1 : Force application points



3.2.2 Blade section loads

The blade thrust force F_T, the blade force torque F_Q and the centrifugal force F_C are to be decomposed at the blade root r_i as shown on Fig 2 in order to calculate strains in the blade laminates.

These forces generate the following forces and moments on the main axes of the blade:

a) Blade thrust force F_T:

- on U axis:

  $F_{T.U} = F_T \cdot \sin\theta_i$

  $F_{T.U}$ generates:

  $M_{FT,U}$: Bending moment, in N.m, around V axis with $(0{,}7R - r_i)$ lever arm, equal to:

  $M_{FT,U} = F_{T.U} \cdot (0{,}7R - r_i)$

  $T_{FT,U}$: Out of shear plane, in N, equal to:

  $T_{FT,U} = F_{T.U}$

- on V axis:

  $F_{T.V} = F_T \cdot \cos\theta_i$

  $F_{T.V}$ generates:

  $M_{FT,V}$: Bending moment, in N.m, around U axis with $(0{,}7R - r_i)$ lever arm, equal to:

  $M_{FT,V} = F_{T.V} \cdot (0{,}7R - r_i)$

  $T_{FT,V}$: Out of shear plane, in N, equal to:

  $T_{FT,V} = F_{T.V}$

b) Blade force torque F_Q:

- on U axis:

  $F_{Q.U} = -F_Q \cdot \sin\theta_i$

  $F_{Q.U}$ generates:

  $M_{FQ,U}$: Bending moment, in N.m, around V axis with $(0{,}66R\text{-}r_i)$ lever arm, equal to:

  $M_{FQ,U} = F_{Q.U} \cdot (0{,}66R - r_i)$

  $T_{FQ,U}$: Out of shear plane, in N, equal to:

  $T_{FQ,U} = F_{Q.U}$

- on V axis:

  $F_{Q.V} = F_Q \cdot \cos\theta_i$

  $F_{Q.V}$ generates:

  $M_{FQ,V}$: Bending moment, in N.m, around U axis with $(0{,}66R - r_i)$ lever arm, equal to:

  $M_{FQ,V} = F_{Q.V} \cdot (0{,}66R - r_i)$

  $T_{FQ,V}$: Out of shear plane, in N, equal to:

  $T_{FQ,V} = F_{Q.V}$

- on Z axis:

  $F_{T.V}$ and $F_{Q,V}$ generate:

  $M_{F,Z}$: Torque moment, in N.m, around Z axis with d_{GU} lever arm, equal to:

  $M_{F,Z} = (F_{T,V} + F_{Q,V}) \cdot d_{GU}$

c) Centrifugal force F_C:

F_C generates:

M_{FCLU} : Bending moment, in N.m, around V axis, equal to:

$M_{FCLU} = F_C \cdot L_U$

M_{FCLV} : Bending moment, in N.m, around U axis, equal to:

$M_{FCLV} = F_C \cdot L_V$

F_{CZ} : Normal force, in N, along Z axis.

where:

R : Radius of the blade, in mm

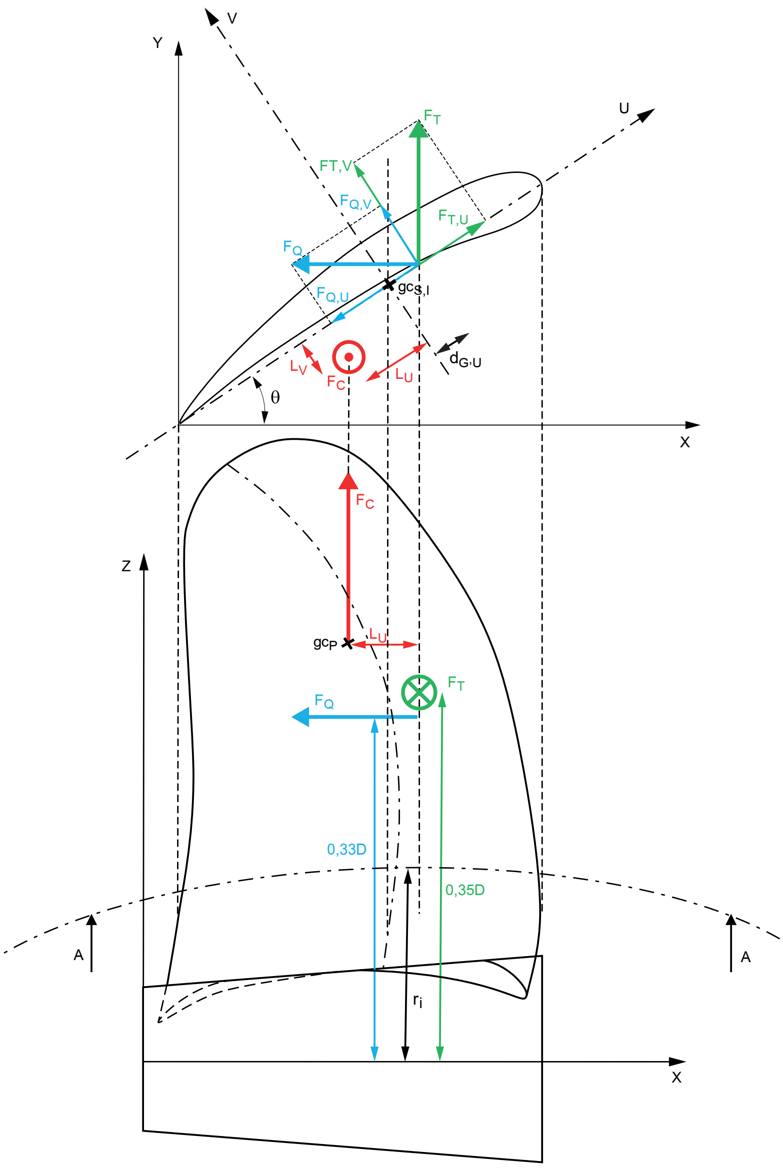
r_i : Radius of the computed section, in mm

L_U, L_V : Lever arm, in mm, for F_C (see Fig 2)

θ_i : Angle, in degree, of the considered section

d_{GU} : Distance, in mm, according to U axis between gravity center of i section and load application point for F_T and F_Q. If d_{GU} is not defined, F_T and F_Q are to be considered as applied on the hydrodynamic center of the blade and inertia centroid of section A-A (d_{GU}=0)

Figure 2 : Forces application



$gc_{s,I}$ stand for gravity centre of the considered section and gc_p for gravity centre of the blade

3.3 Loads to be considered for numerical calculation method - Final design

3.3.1 General

The numerical method is to be based on the Boundary Element Method (BEM) or on the Computational Fluid Dynamics (CFD) computations in order to determined the pressure distribution, and on finite element analysis to evaluate stresses.

This methodology will permit to assess the final scantling of the blade propeller.

3.3.2 Continuous maximum speed loads

Loads calculated at continuous maximum speed are defined in [3.1].

3.4 Loads for fatigue calculations

3.4.1 Fluctuation loads

Fluctuations loads are the loads effective on one revolution of propeller blade which are generated by:

- difference of maximum and minimum thrust due to non uniform wakefield
- buoyancy effect.

These loads are to be defined by the designer.

3.5 Blade-hub connection loading

3.5.1 Design loads considered at the interface between blades and hub are the loads defined in [3.2] and [3.3] and applied at the blade root.

4 Strength analysis

4.1 Propeller blade basic design - Analytical method

4.1.1 Loading

a) Calculation points:

At least, two sections are to be assessed, one at 0,25R and the second at 0,6R.

For non conventional propeller (highly skewed propeller), special considerations are to be taken according to the blade design and additional sections may be assessed upon Society's request.

b) Forces and bending moments:

Forces and bending moments are to be calculated as defined in [3.2].

4.1.2 Blade section

For the followings, reference is made to ComposeIT, a calculation software developed by Bureau Veritas enabling users to perform detailed strength analyses of composite materials. Other applications and methodology may be considered by the Society.

a) Blade section stresses are obtained by loading the laminate of the blade section with strain, shear strain and shear force, as described in c), with ComposeIT.

b) Referential and units:

To be in accordance with ComposeIT calculations, a change of referential from (U,V,Z) to (x,y,z) is to be performed according to Fig 3.

Forces N_X, N_y, N_{XY}, T_{XZ}, T_{YZ} and bending moments M_X, M_Y, M_Z are to be expressed per unit length (respectively in kN/m and kN.m/m) in the referential (x,y,z).

Displacements ε_x, ε_y, ε_z are expressed in % in the referential (x,y,z).

c) The strength analysis of laminates located at calculation point with coordinate $d_{i,u}$ and $d_{i,v}$, corresponding to extrados (suction side) and intrados (pressure side), is to be determined considering the strains in ε_x (in x direction) and γ_{xy} (in xy directions), in %:

$$\varepsilon_X = \frac{(M_{FT,U} + M_{FQ,U}) d_{iu} 10^5}{[E_X I_U]} - \frac{(M_{FT,V} + M_{FQ,V}) d_{iv} 10^3}{[E_X I_V]} + \frac{F_C 10^2}{[E_X A_Z]}$$

$$\gamma_{XY} = \frac{-M_{F,Z} d_{iu} 10^3}{[G_Z I_Z]} - \frac{F_{T,U} + F_{Q,U}}{[G_Z A_Z]}$$

and the transverse shear forces T_{YZ}, in N/mm, to determined the interlaminar shear stresses:

$$T_{YZ} = \frac{T_{FT,V} + T_{FQ,V}}{2 C_p}$$

where:

A_Z : Profile cross section area, in mm²

C_p : Profile chord length, in mm

di_U, di_V : Distance, in mm, between neutral axis (according respectively to I_v and I_u) to the position of calculation point with sign convention as per described on Fig 4.

I_U : Inertia, in mm⁴, according to U axis taken from CAO model

I_V : Inertia, in mm⁴, according to V axis taken from CAO model

I_Z : Inertia, in mm⁴, according to Z axis taken from CAO model

E_X : Young modulus, in MPa, of laminates constituting the section

G_Z : Shear modulus, in MPa, of laminates constituting the section

F_T, F_Q, F_C: Forces in N defined in [3.2]

$[E_X.I_U]$: Bending rigidity of profile, in N.mm², according to U axis taken as the product of E_X Young modulus, in MPa, of laminates constituting the section per I_U inertia, in mm⁴

$[E_X.I_V]$: Bending rigidity of profile, in N.mm², according to V axis taken as the product of E_X Young modulus, in MPa, of laminates constituting the section per I_V inertia, in mm⁴

$[E_X.A_Z]$: Tensile rigidity of profile, in N.mm², according to V axis taken as the product of E_X Young modulus, in MPa, of laminates constituting the section per A_Z, profile cross section in mm²

$[G_Z.I_Z]$: Torsional rigidity of the profile, in N.mm², according to Z axis taken as the product of G_Z Shear modulus, in MPa, of laminates constituting the section per I_Z inertia, in mm⁴

$[G_Z.A_Z]$: Shear rigidity of the profile, in N, according to z axis.

Note 1: For calculation of product $[E_X.I_U]$, $[E_X.I_V]$, $[G_Z.I_Z]$, $[G_Z.A_Z]$, the approach developed here above is only available for section with homogeneous and constant laminate composition.

Sections with local reinforcement will be subject to a case-by-case basis approach for the calculation of bending, torsional and shear rigidity.

4.2 Final design - Numerical method

4.2.1 Hydrodynamic open-water computations

The first stage consists in to determine the hydrodynamic pressures applied on the propeller using dedicated software.

The hydrodynamic calculation methodology described hereafter is provided as a guidance. Other methodologies are to be submitted to the Society for approval on a case-by-case basis.

Figure 3 : Load axis definition for ComposeIT software

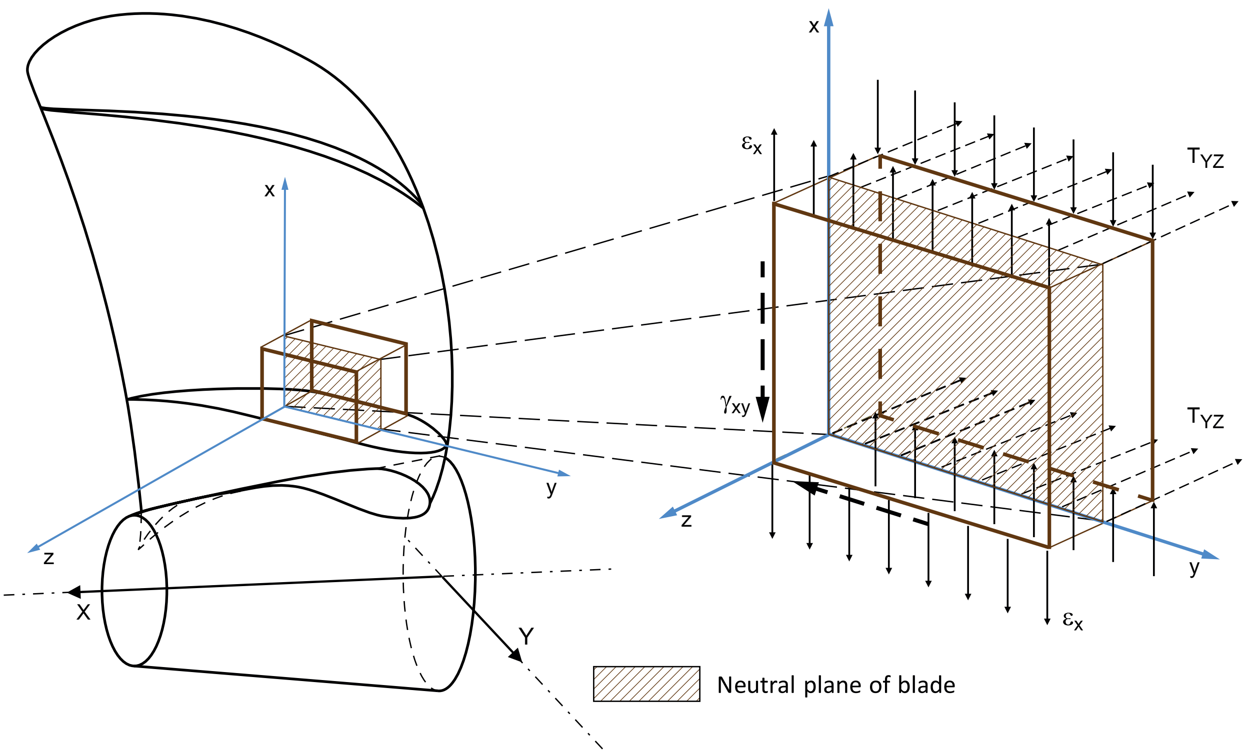
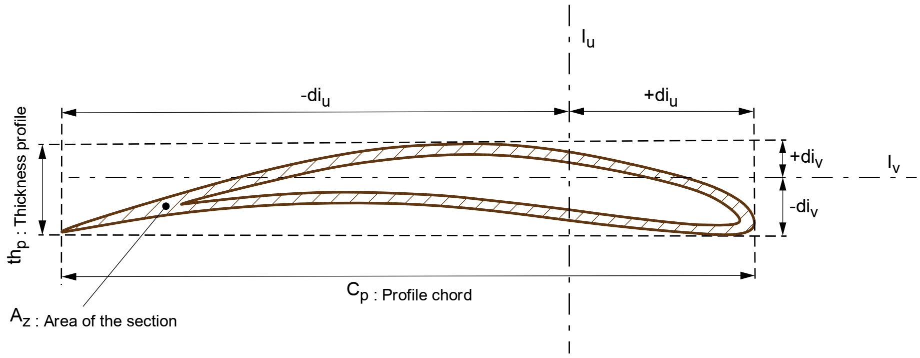


Figure 4 : Geometry



a) Numerical solvers:

The hydrodynamic loads may be determined with hydrodynamic calculations solving Reynolds Averaged Navier-Stokes Equations (RANSE). The RANSE solvers are more commonly referred as Computational Fluid Dynamics (CFD) and the computations should be performed at full scale on the exact propeller geometry. Any induced load difference is to be evaluated in case on geometrical simplifications, compared to the manufactured propeller, for the purpose of computations.

The results obtained with the numerical solver are to be duly justified by comparison with experiments on similar applications, and be submitted to the Society.

Any other approach for loads evaluation, i.e. Boundary Element Method (BEM), might be accepted on a case by case basis by the Society.

b) Convergence studies:

The validity of the CFD model should be evaluated by performing:

- a mesh convergence study
- the evaluation of influence of y+
- a time-step convergence study.

The aim of these computations is to verify that the physics involved in the propeller rotation are accurately captured.

Note 1: The dimensionless wall distance y^+ defines how the flow in the boundary layer is computed and is equal to:

$y^+ = u^* \cdot y / v$

where:

y	:	Distance of the first cell to the nearest wall
u^*	:	Friction velocity at the nearest wall
v	:	Local kinematic viscosity of the fluid

In case of flow detachments, meshing with y^+ lower than 1 is recommended. Otherwise, the viscous sub-layer is not solved, and the accurate evaluation of detachment is impossible.

For flow without detachment, meshing with y^+ greater than 30 is recommended, in order to keep a reasonable size of mesh and evaluate viscous forces with wall functions

c) Meshing:

The following points are prerequisite to ensure the flow is accurately captured around the propeller blades:

- Sufficiently fine discretization of the leading and trailing edges as well as the blade roots and tips in order to capture accurately the blade geometry at these critical locations
- Volume mesh refinement implemented in the propeller wake.

d) Compatibility with finite element model setup:

The surface mesh of the blade in the hydrodynamic model is to be built in order to allow the transfer of pressure field to a Finite Element Model (FEM) described in [4.2.2], either:

- by splitting the surface mesh used in CFD in parts that will represents elements in future FEM model
- by enabling the export of the pressure field from CFD to FEM model with an adapted file format
- by using a mapping procedure implemented in the code.

e) Input data for open-water computations:

The following input data used for CFD computations should be provided:

- Propeller CAD with separated pressure and suction sides of the blades
- Hub and shaft simplified CAD geometry (a semi-infinite shaft can be used)
- Advance ratio (rotation speed vs forward speed),
- Scale of computations if applicable.

Note 2: As a guidance, computations are recommended to be performed at full scale in order to correctly predict the laminar-turbulent transition on the blades.

f) Numerical model:

The choice of the numerical model used to represent the propeller depends on the constraints on motion of the problem

Moving Reference Frame: the mesh is static and the propeller rotation is solved in a moving reference frame:

- Calculation with cyclic model, representing only one blade and using periodic boundary conditions on side boundaries
- Calculation in full domain, representing all blades

Rigid Body Motion: the mesh of the propeller is rotating in the domain:

- Calculation in full domain with a sliding grid, when both fixed and rotating parts are modelled.

g) Output data:

Hydrodynamic calculations provide:

- Pressure fields exerted on pressure and suction sides of blades. The pressure field is applied on Finite Element Model (FEM) described in [4.2.2]
- Propeller loads (thrust and torque).

4.2.2 Finite element calculation

In the second stage, a Finite Element Model (FEM) is to be carried out representing the mechanical behaviour of the blade and its connection to the shaft line.

a) Numerical solvers:

Finite elements models are generally based on linear assumptions however geometrical non linearity is to be considered due to the deflection of the blade induced by hydrodynamic loads.

The results obtained with the mechanical solver are to be justified on similar applications, and validation is to be submitted to the Society

b) Materials:

Material properties are to be considered layer by layer according to NR546 requirements. Laminate plate or solid elements should be used to account for the coupling between membrane and bending effect. Any other arrangement, i.e. homogeneous properties, might be accepted on a case by case basis by the Society.

c) Meshing:

The mesh is to be defined using laminate shell or solid elements, with or without mid-side nodes. Meshing is to be carried out following uniformity criteria among the different elements.

The blade and the hub connection is to be carefully meshed and results are to be validated by test (see Sec 5).

Boundary conditions should be representative as much as possible to the blade connections with the hub or the rotor. For connection made by bolts, laminate area in contact with bolts should be checked against in plane forces (bearing loads), out of plane forces (tightening of bolts) and other forces/moments depending of bolting configuration.

d) Loads:

Hydrodynamic loads computed by CFD in [4.2.1] are applied on pressure side and suction side.

Blade thrust and blade torque forces obtained by CFD and applied in FEM are to be checked and must be the same

The centrifugal forces related to the rotation of the blades are to be evaluated and incorporated unless demonstrated as not relevant. The centrifugal added stiffness should be considered upon its proportion in the total load.

e) Post processing:

Following stresses are to be post-processed layer by layer in accordance with App 2:

- Main stresses in the individual layers (in fibre direction, perpendicular to fibre direction and shear)
- Combined stresses in each layer using a Hoffman criteria. Tsaï Wu or equivalent criteria might be used with Society agreement
- Interlaminar shear stresses
- Buckling stresses

For all stresses, maximum tension and maximum compression stresses shall be duly assessed and compared with safety factor defined in [2].

f) A modal analysis is to be performed to evaluate natural frequencies and associated mode shapes:

- in air for the control of the full scale blade stiffness in Sec 5, [3.1.1]
- in water to determine wet modes and to avoid resonance issues.

It should be shown that no interference may occur with the main excitation frequencies among which: rotational speed, shaft bracket wake frequency.

5 Connection between hub and blade

5.1 General

5.1.1 In case of bolting of propeller blades to the hub, special attention is to be paid on:

- tightening torque applied on bolts
- bolts tensioning sequence and method
- bolt fatigue
- bolt nut, washer type, dimension, material and quality.

Special care must be taken in order to prevent any galvanic corrosion effect due to the presence of different materials.

5.1.2 Other connection system

Other connections system like dovetail, clamping flange will be subject to special consideration on case-by-case basis.

5.1.3 Scantling

For connection made by bolts, laminate area in contact with bolts should be checked against in plane forces (bearing loads), out of plane forces (tightening of bolts) and other forces / moments depending of bolting configuration.

6 Fatigue analysis methodology

6.1 General

6.1.1 When deemed necessary by the Society, fatigue analysis is to be assessed for the blade itself and its connection to the Hub.

For composite blade material, the fatigue analysis is to be based on the S/N curve for a specified R ratio (R ratio is defined as the minimum stress divided by the maximum stress).

6.1.2 Fatigue loading

The S/N curves obtained for R ratios relevant for the loading cases considered are to be submitted. If the blade is subject to fatigue stresses of other R ratios than the S/N curves, a constant amplitude lifetime calculation method, or diagram, is to be submitted.

The cyclic stresses are mainly the cyclic stresses induced by the fluctuating loads as per described in [3.4]. Other cyclic stresses induced by other effect such as buoyancy are also to be taken into account.

As a rule, only the cyclic stresses induced by normal and continuous operations are to be taken into account. For each considered loading, the mean stress, the amplitude of the vibratory stress and the required number of cycles are to be specified.

6.1.3 Total damage

The total damage ratio D is the sum of each elementary damage ration D; corresponding to each specific loading cases.

The total damage ratio D may be calculated with the Miner's damage accumulation rule and is to satisfy:

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_{Ri}} \leq \frac{1}{SF_f}$$

where:

n_i : Required number of cycles for the cyclic loading considered

N_{Ri} : Number of cycles necessary to the failure for cyclic loading considered

SF_f : Safety factor to be defined on a case by case basis.

6.2 Full scale fatigue tests

6.2.1 Full scale fatigue tests are to be performed when:

- no fatigue analysis is provided by designer and,
- requirements of [2.4.2] are not fulfilled.

When full scale fatigue tests are carried out, the fatigue test conditions are to be submitted to the Society for examination.

Section 7 Arrangement, Installation and Sea Trials

1 Arrangement and installation

1.1 Coating protection of propeller

1.1.1 As a general rule, composite blades are protected by a coating in order to prevent:
- water ingress in laminate
- bio fouling.
- risk of erosion by changing surface properties with regards to its abrasion resistance

and to improve hydrodynamic efficiency.

Coating should be compatible with constituents of the propeller blade itself. It should be applied as a top coat or a gel-coat.

1.2 Cathodic protection adapted (consideration of the composites propeller)

1.2.1 Means are to be provided to prevent circulating electric currents from developing between the propeller and the hull. A description of the type of protection and its maintenance is to be kept on board.

1.3 Up-grading of an existing propulsion system

1.3.1 In case of change of propeller from cast to composite materials, following data and report are to be submitted for approval:
- shaft alignment calculation report
- whirling calculation of the line shafting
- rudder loads
- cathodic protection.

1.4 Fitting on the composite materials blade on the hub (built-up propeller)

1.4.1 Generality

Means are to be provided in order to ensure a good contact surface between blade and hub. Chocking system might be fitted provided that justifications of scantling are submitted.

In all case a system permitting to ensure watertightness of the contact surface is to be fitted, more particularly in case of hollow blade profile. This system might also be used for protection against galvanic corrosion at the contact surface.

1.4.2 Tightened connection

For blades connected by tightening up (bolts or clamping devices), adjustment of tightening is to be controlled in order to avoid any crushing of composite part subject to compression effect.

A particular attention is to be taken for potential stress concentration in way of tightening system. Fatigue checks are to be performed in this area.

1.4.3 Other type of connection

Installation of propeller with other type of connection will be subject to a review based on a case by case basis. A detailed procedure showing mounting arrangement is to be submitted before mounting.

1.5 Fitting of the hub on the propeller shaft

1.5.1 Metallic hub

Requirements for the arrangement and the fitting of metallic hub are given in NR467, Pt C, Ch 1, Sec 8, [3]. In case where hub is stressed by shrinking, it shall be checked that induced stresses will not affect blade hub connection.

1.5.2 Composite hub

Arrangement and fitting of propeller with composite hub will be subject to special consideration depending on type of mounting.

2 Sea trials

2.1 General

2.1.1 The sea trials are intended to demonstrate that the propeller is functioning properly according to the criteria defined in NR467, Pt C, Ch 1, Sec 18.

The tests are to be witnessed by the Society.

2.1.2 The sea trials procedure is to be submitted to the Society before testing.

The sea trials procedure should include informations such as:

- aims of the sea trials
- organization of sea trials (date, attendees)
- sea trials conditions (place, weather and environmental conditions..)
- procedure of test (duration of the tests, checks)
- control and measurement, measurement results.

The testing procedure shall include tests that are representative of ship manoeuvring (i.e.giration, crash stop, manoeuvring ahead and astern…).

Section 8 In-Service Surveys

1 General

1.1 Survey principles

1.1.1 Requirements of NR467, Part A dedicated to metallic propeller are applicable as far as they are relevant for a propeller made of composite.

Periodicity of surveys will be defined by the Society in accordance with design and on case-by-case basis.

1.2 Scope of survey

1.2.1 For composite materials propeller an external examination of the coating condition is to be carried-out. This examination is to be directed at discovering significant alteration of the coating or contact damages. If any and if deemed necessary, NDT testing might be requested by the Society.

Particular attention is to be paid of the following parts of the blade:

- leading edge
- trailing edge
- connection system

Based on records of NDT tests as per mentioned in Sec 5, [3.1.1], a comparative analysis might be performed, where deviations will be submitted to the Society for acceptance.

Appendix 1 Individual Layers for Laminates

1 General

1.1 Application

1.1.1 General

The scantling check of a laminate (based on geometrical characteristics and on plane elastic coefficients of the laminate) is carried out calculating the safety factors in each layer as defined in Sec 6, [2].

The present Appendix deals with the methodology to determine the theoretical breaking stresses of the individual layers, necessary to calculate the safety factors.

The theoretical breaking stresses of individual layer considered are:

- in-plane longitudinal tensile and compression breaking stresses
- in-plane transverse tensile and compression breaking stresses
- in-plane shear breaking stress
- interlaminar shear breaking stress.

1.1.2 Methodology

Whatever the type of reinforcement making up the individual layer, the first step of the methodology consists in estimating the elastic coefficients of an equivalent unidirectional (UD) fabric having the same raw materials and content of fibre as the individual layer to be calculated, according to [3.1].

The elastic coefficients of a woven roving (WR) or a shopped strand mat (CSM) are calculated according to [3.2] and [3.3] respectively, on the basis of the elastic coefficients of the equivalent UD.

The elastic coefficients and breaking stress parameters defined in the present Appendix are based on the Society experience and take into account the:

- type of raw material
- fibre/resin mix ratio, depending on the type of reinforcement and the laminating process
- type of stress in relation to the reinforcement orientation.

1.1.3 Specific methodology

Where unusual individual layers are used, due to specific raw materials or laminating process, the Society may request mechanical tests to be performed in order to evaluate elastic coefficients and breaking stresses and compare them to the present theoretical approach.

1.1.4 Symbols

$E_{f0°}$: Longitudinal Young modulus of fibre in the axis parallel to the fibre direction, in N/mm^2

$E_{f90°}$: Transverse Young modulus of fibre in the axis perpendicular to the fibre direction, in N/mm^2

E_r : Young modulus of resin, in N/mm^2

G_f : Shear modulus of fibre, in N/mm^2

G_r : Shear modulus of resin, in N/mm^2

ρ_f : Density of fibre

ρ_r : Density of resin

ν_f : Poisson coefficient of fibre

ν_r : Poisson coefficient of resin

M_f : Content in mass of fibre in an individual layer, in % (see [2.1])

M_r : Content in mass of resin in an individual layer, in % (see [2.1])

P_f : Total mass per square meter of dry reinforcement fabric, in g/m^2

V_f : Content in volume of fibre in an individual layer, in % (see [2.1])

V_r : Content in volume of resin in an individual layer, in % (see [2.1])

ρ : Density of an individual layer (see [2.3])

e : Individual layer thickness, in mm (see [2.2.1])

C_{eq} : Woven balance coefficient for woven rovings (see [3.2]).

2 Geometrical and physical properties of an individual layer

2.1 Fibre/resin mix ratios

2.1.1 The fibre/resin mix ratios, which express the amount of fibres and/or resins in an individual layer, may be expressed in:

- mass or volume, and
- resin or reinforcement.

The contents in mass of fibre M_f and in mass of resin M_r are obtained from the following formulae:

M_f = fibre mass (g/m^2) / individual layer mass (g/m^2)

M_r = resin mass (g/m^2) / individual layer mass (g/m^2).

The contents in volume V_f and V_r , and the contents in mass M_f and M_r are deduced from each other by:

$$V_f = \frac{M_f / \rho_f}{M_f / \rho_f + (1 - M_f) / \rho_r}$$

$$V_r = 1 - V_f$$

$$M_f = \frac{V_f \cdot \rho_f}{V_f \cdot \rho_f + (1 - V_f) \cdot \rho_r}$$

$$M_r = 1 - M_f$$

The resin/fibre mix ratios are to be specified by the manufacturer and depend on the laminating process.

2.2 Individual layer thickness

2.2.1 The individual layer thickness, in mm, may be expressed from the fibre content, in mass or in volume, by the following formulae:

$$e = \frac{P_f \cdot \left(\frac{1}{\rho_f} + \frac{1 - M_f}{M_f \cdot \rho_r}\right)}{1000}$$

$$e = \frac{P_f \cdot \left(\frac{1}{V_f \cdot \rho_f}\right)}{1000}$$

2.3 Density and individual layer

2.3.1 For information, the density of an individual layer is obtained from the following formula:

$$\rho = \rho_f \cdot V_f + \rho_r \cdot (1 - V_f)$$

3 Elastic coefficients of an individual layer

3.1 Unidirectional

3.1.1 Reference axis

The reference axis system for an unidirectional is shown on Fig 1.

The reference axis system for an elementary fibre is shown on Fig 2.

Figure 1 : Reference axis system for an unidirectional

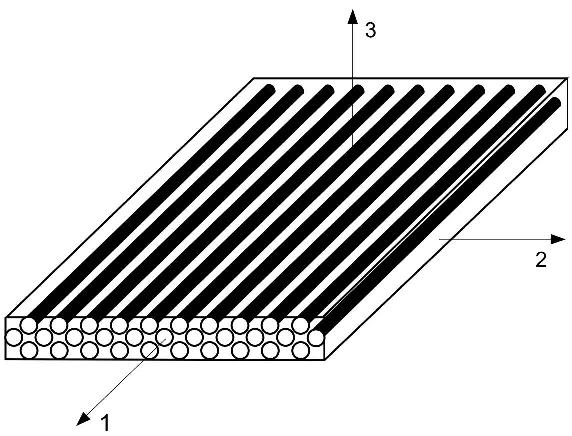
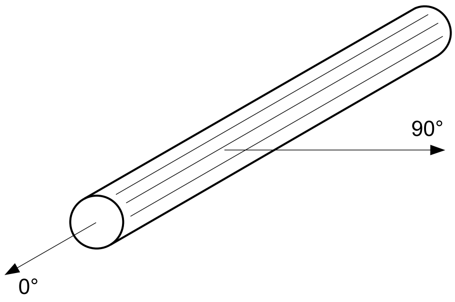


Figure 2 : Reference axis system of an elementary fibre



0° : Longitudinal axis of the fibre

90° : Transverse axis of the fibre.

3.1.2 Elastics coefficients

The elastic coefficients of an unidirectional are estimated by the following formulae:

- longitudinal Young modulus E_{UD1}, in N/mm²:

$$E_{UD1} = C_{UD1} \cdot [E_{f0°} \cdot V_f + E_r \cdot (1 - V_f)]$$

- transverse Young moduli E_{UD2} and E_{UD3}, in N/mm²:

$$E_{UD2} = E_{UD3} = C_{UD2} \cdot \left[\left(\frac{E_r}{1 - \nu_r^2}\right) \cdot \frac{1 + 0,85 \cdot V_f^2}{(1 - V_f)^{1,25} + \frac{E_r}{E_{f90°}} \times \frac{V_f}{1 - \nu_r^2}}\right]$$

- shear moduli G_{UD12}, G_{UD13} and G_{UD23}, in N/mm²:

$$G_{UD12} = G_{UD13} = C_{UD12} \cdot G_r \cdot \frac{1 + \eta \cdot V_f}{1 - \eta \cdot V_f}$$

$$G_{UD23} = 0,7 \cdot G_{UD12}$$

with $$\eta = \frac{\left(\frac{G_f}{G_r}\right) - 1}{\left(\frac{G_f}{G_r}\right) + 1}$$

- poisson coefficients:

$$\nu_{UD13} = \nu_{UD12} = C_{UD\nu} \cdot [\nu_f \cdot V_f + \nu_r \cdot (1 - V_f)]$$

$$\nu_{UD21} = \nu_{UD31} = \nu_{UD12} \cdot \frac{E_{UD2}}{E_{UD1}}$$

$$\nu_{UD23} = \nu_{UD32} = C_{UD\nu} \cdot [\nu_f' \cdot V_f + \nu_r \cdot (1 - V_f)]$$

with $$\nu_f' = \nu_f \cdot \frac{E_{f90°}}{E_{f0°}}$$

Coefficients C_{UD1}, C_{UD2}, C_{UD12} and $C_{UD\nu}$ (see Tab 1) are experimental coefficients taking into account the specific characteristics of fibre type.

Table 1 : Coefficients C_{UD1}, C_{UD2}, C_{UD12} and $C_{UD\nu}$

	E-glass	R-Glass	Carbon HS	Carbon IM	Carbon HM	Para-aramid
C_{UD1}	1,0	0,9	1,0	0,85	0,90	0,95
C_{UD2}	0,8	1,2	0,7	0,80	0,85	0,90
C_{UD12}	0,9	1,2	0,9	0,90	1,00	0,55
$C_{UD\nu}$	0,9	0,9	0,8	0,75	0,70	0,90

3.2 Woven roving

3.2.1 Reference axis

The reference axis system defined for a woven roving is the same as for an unidirectional, with the following denomination:

1 : Axis parallel to warp direction

2 : Axis parallel to weft direction

3 : Axis normal to the plane containing axes 1 and 2, leading to the direct reference axis system.

3.2.2 Woven balance coefficient C_{eq}

The woven balance coefficient C_{eq} is equal to the mass ratio of dry reinforcement in warp direction to the total dry reinforcement of woven fabric.

3.2.3 Elastic coefficients

The elastic coefficients of a woven roving as individual layer are estimated by the following formulae:

- young modulus in warp direction E_{T1}, in N/mm^2:

$$E_{T1} = \frac{1}{e} \cdot \left(A_{11} - \frac{A_{12}^2}{A_{22}}\right)$$

- young modulus in weft direction E_{T2}, in N/mm^2:

$$E_{T2} = \frac{1}{e} \cdot \left(A_{22} - \frac{A_{12}^2}{A_{11}}\right)$$

- out-of-plane Young modulus E_{T3}, in N/mm^2:

$$E_{T3} = E_{UD3}$$

- shear moduli G_{T12}, G_{T13} and G_{T23}, in N/mm^2:

$$G_{T12} = \frac{1}{e} \cdot A_{33}$$

$$G_{T13} = G_{T23} = 0,9 \cdot G_{T12}$$

- poisson coefficients:

$$\nu_{T12} = \frac{A_{12}}{A_{22}}$$

$$\nu_{T21} = \nu_{T12} \cdot \frac{E_{T2}}{E_{T1}}$$

$$\nu_{T32} = \nu_{T31} = \frac{\nu_{UD32} + \nu_{UD31}}{2}$$

$$\nu_{T13} = \frac{\nu_{UD23} + \nu_{UD13}}{2}$$

where:

$$A_{11} = e \cdot [C_{eq} \cdot Q_{11} + (1 - C_{eq}) \cdot Q_{22}]$$

$$A_{22} = e \cdot [C_{eq} \cdot Q_{22} + (1 - C_{eq}) \cdot Q_{11}]$$

$$A_{12} = e \cdot Q_{12}$$

$$A_{33} = e \cdot Q_{33}$$

with:

$$Q_{11} = \frac{E_{UD1}}{1 - \nu_{UD12} \cdot \nu_{UD21}}$$

$$Q_{22} = \frac{E_{UD2}}{1 - \nu_{UD12} \cdot \nu_{UD21}}$$

$$Q_{12} = \frac{\nu_{UD21} \cdot E_{UD1}}{1 - \nu_{UD12} \cdot \nu_{UD21}}$$

$$Q_{33} = G_{UD12}$$

Note 1: Parameters with suffix UD are the values defined in [3.1] for an UD having the same raw materials and mix ratios as the woven roving under calculation.

3.3 Chopped strand mat

3.3.1 General

A chopped strand mat is assumed to be an isotropic material.

3.3.2 Elastic coefficients

Isotropic assumption allows to define the elastic coefficients of a chopped strand mat with the following formulae:

- young moduli, in N/mm²:

$$E_{mat1} = E_{mat2} = \frac{3}{8} \cdot E_{UD1} + \frac{5}{8} \cdot E_{UD2}$$

$$E_{mat3} = E_{UD3}$$

- shear moduli, in N/mm²:

$$G_{mat12} = \frac{E_{mat1}}{2 \cdot (1 + \nu_{mat21})}$$

$$G_{mat23} = G_{mat31} = 0,7 \cdot G_{UD12}$$

- poisson coefficients:

$$\nu_{mat12} = \nu_{mat21} = \nu_{mat32} = \nu_{mat13} = 0,3$$

Note 1: Parameters with suffix UD are the values defined in [3.1] for an UD having the same raw materials and mix ratios as the mat under calculation.

3.4 Combined fabric

3.4.1 A combined fabric, made from different woven roving and/or UD stitched together is to be considered as a series of individual layers such as unidirectionals, woven rovings or chopped strand mats. Each component is analysed as defined in [3.1], [3.2] or [3.3], according to the type of reinforcement fabric.

4 In-plane rigidity and flexibility of an individual layer

4.1 In-plane characteristics

4.1.1 Rigidity

The rigidity R, defined in the individual layer coordinate system, is as follows:

$$[\sigma]_{1,2} = [\bar{R}] \cdot [\varepsilon]_{1,2}$$

equivalent to, under matrix notation:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} \bar{R}_{11} & \bar{R}_{12} & 0 \\ \bar{R}_{21} & \bar{R}_{22} & 0 \\ 0 & 0 & \bar{R}_{33} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}$$

where:

[σ] : Matrix of in-plane stresses

[ε] : Matrix of in-plane strains

[R] : Local matrix of rigidity.

Elements of the matrix of rigidity are specific to the types of reinforcement fabrics and are defined in Tab 2.

4.1.2 Flexibility

The flexibility S, defined in the individual layer coordinate system, is as follows:

$$[\varepsilon]_{1,2} = [\bar{S}] \cdot [\sigma]_{1,2}$$

equivalent to, under matrix notation:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} \bar{S}_{11} & \bar{S}_{12} & 0 \\ \bar{S}_{21} & \bar{S}_{22} & 0 \\ 0 & 0 & \bar{S}_{33} \end{bmatrix} \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}$$

where:

[σ] : Matrix of in-plane stresses

[ε] : Matrix of in-plane strains

[S] : Local flexibility matrix of the individual layer.

Elements of the matrix of flexibility are specific to the types of reinforcement fabrics and are defined in Tab 3.

Table 2 : Elements of matrix of rigidity

	For unidirectionals (UD)	For woven rovings (WR)	For mats (CSM)	Core material
R11	$E_{UD1}/(1 - \nu_{UD12} \cdot \nu_{UD21})$	$E_{T1}/(1 - \nu_{T12} \cdot \nu_{T21})$	$E_{mat1}/(1 - \nu_{mat12}^2)$	$E_1/(1 - \nu_{12} \cdot \nu_{21})$
R22	$E_{UD2}/(1 - \nu_{UD12} \cdot \nu_{UD21})$	$E_{T2}/(1 - \nu_{T12} \cdot \nu_{T21})$	$E_{mat2}/(1 - \nu_{mat21}^2)$	$E_2/(1 - \nu_{12} \cdot \nu_{21})$
R12	$\nu_{UD21} \cdot E_{UD1}/(1 - \nu_{UD12} \cdot \nu_{UD21})$	$\nu_{T21} \cdot E_{T1}/(1 - \nu_{T12} \cdot \nu_{T21})$	$\nu_{mat21} \cdot E_{mat1}/(1 - \nu_{mat12}^2)$	$\nu_{21} \cdot E_1/(1 - \nu_{12} \cdot \nu_{21})$
R21	$\nu_{UD12} \cdot E_{UD2}/(1 - \nu_{UD12} \cdot \nu_{UD21})$	$\nu_{T12} \cdot E_{T2}/(1 - \nu_{T12} \cdot \nu_{T21})$	$\nu_{mat12} \cdot E_{mat2}/(1 - \nu_{mat21}^2)$	$\nu_{12} \cdot E_2/(1 - \nu_{12} \cdot \nu_{21})$
R33	G_{UD12}	G_{T12}	G_{mat12}	G_{12}

Table 3 : Elements of matrix of flexibility

	For unidirectionals (UD)	For woven rovings (WR)	For mats (CSM)	Core material
S11	$1/E_{UD1}$	$1/E_{T1}$	$1/E_{mat}$	$1/E_1$
S22	$1/E_{UD2}$	$1/E_{T2}$	$1/E_{mat}$	$1/E_2$
S12	$-\nu_{UD21}/E_{UD2}$	$-\nu_{T21}/E_{T2}$	$-\nu_{mat}/E_{mat}$	$-\nu_{21}/E_2$
S21	$-\nu_{UD12}/E_{UD1}$	$-\nu_{T12}/E_{T1}$	$-\nu_{mat}/E_{mat}$	$-\nu_{12}/E_1$
S33	$1/G_{UD12}$	$1/G_{T12}$	$1/G_{mat12}$	$1/G_{12}$

5 In-plane theoretical individual layer breaking stresses

5.1 Definitions

5.1.1 Theoretical breaking stress calculations

The in-plane theoretical individual layer breaking stresses are defined, in N/mm², as the maximum breaking stresses of the individual layer in its local coordinate system, taking into account the type and the direction of the stresses. The theoretical breaking stresses are obtained from the following formulae:

$\sigma_{brt1} = \varepsilon_{brt1} \cdot E_1 \cdot Coef_{res}$

$\sigma_{brc1} = \varepsilon_{brc1} \cdot E_1 \cdot Coef_{res}$

$\sigma_{brt2} = \varepsilon_{brt2} \cdot E_2 \cdot Coef_{res}$

$\sigma_{brc2} = \varepsilon_{brc2} \cdot E_2 \cdot Coef_{res}$

$\tau_{br12} = \gamma_{br12} \cdot G_{12} \cdot Coef_{res}$

$\tau_{brIL1} = \gamma_{brIL1} \cdot G_{23} \cdot Coef_{res}$

$\tau_{brIL2} = \gamma_{brIL2} \cdot G_{13} \cdot Coef_{res}$

where:

E_1, E_2, G_{12}, G_{13}, G_{23} : Elastic coefficients defined in [3], in N/mm², for the individual layer considered according to the type of reinforcement (UD, WR, CSM)

$Coef_{res}$: Coefficient taking into account the adhesive quality of the resin system, as defined in Tab 4.

Table 4 : Coefficient $Coef_{res}$

Resin systems		
Polyester	Vinylester	Epoxy
0,8	0,9	1,0

ε_i, γ_i : Theoretical breaking strains, in %, given in Tab 5, defined as follow:

ε_{brt1}, ε_{brc1} : Theoretical breaking strains, in %, respectively in tensile and in compression, of an individual layer in direction 1 of its local coordinate system

ε_{brt2}, ε_{brc2} : Theoretical breaking strains, in %, respectively in tensile and in compression, of an individual layer in direction 2 of its local coordinate system

γ_{br12} : Theoretical in-plane breaking shear strain, in %, of an individual layer

γ_{brIL} : Theoretical interlaminar breaking shear strain, in %, of an individual layer.

5.1.2 As a general rule, mechanical characteristics of an individual layer are also depending on the laminating process. In order to simplify calculations of the theoretical breaking stresses defined in [5.1.1], the influence of the laminating process is taken into account by means of a dedicated safety factor (C_F) defined in Sec 6, applied to the whole laminate.

6 Other breaking stress approach

6.1 General

6.1.1 Other breaking stresses approach

Other maximum breaking stress values of individual layers may be taken into account provided that representative mechanical tests are submitted to the Society for examination.

6.1.2 Other raw materials for individual layers

When other raw materials than those defined in Sec 3 are used for individual layers, the different values of breaking stresses listed in [5.1.1] are to be submitted. These values may be obtain by representative mechanical tests.

Table 5 : Theoretical breaking strains, in %

Reinforcement fabric type	Strains		Reinforcement fibre type: E Glass	R Glass	HS Carbon	IM Carbon	HM Carbon	Para-aramid
Unidirectionals	Tensile	ε_{brt1}	2,70	3,10	1,20	1,15	0,70	1,70
		ε_{brt2}	0,53	0,44	1,00	0,80	0,50	0,80
	Compression	ε_{brc1}	1,80	1,80	0,85	0,65	0,45	0,35
		ε_{brc2}	1,55	1,10	2,30	2,30	2,10	2,00
	Shear	γ_{br12}	1,80	1,50	1,60	1,70	1,80	2,00
		γ_{br13} γ_{brIL2}	1,80	1,50	1,60	1,70	1,80	2,00
		γ_{br23} γ_{brIL1}	2,50	1,80	1,90	1,85	1,80	2,90
Woven rovings	Tensile	ε_{brt1}	1,80	2,30	1,00	0,80	0,45	1,40
		ε_{brt2}	1,80	2,30	1,00	0,80	0,45	1,40
	Compression	ε_{brc1}	1,80	2,50	0,85	0,80	0,50	0,42
		ε_{brc2}	1,80	2,50	0,85	0,80	0,50	0,42
	Shear	γ_{br12}	1,50	1,50	1,55	1,60	1,85	2,30
		γ_{br13} γ_{brIL2}	1,80	1,80	1,55	1,60	1,85	2,90
		γ_{br23} γ_{brIL1}	1,80	1,80	1,55	1,60	1,85	2,90
Chopped strand mats	Tensile	ε_{brt1}	1,55	NA	NA	NA	NA	NA
		ε_{brt2}	1,55	NA	NA	NA	NA	NA
	Compression	ε_{brc1}	1,55	NA	NA	NA	NA	NA
		ε_{brc2}	1,55	NA	NA	NA	NA	NA
	Shear	γ_{br12}	2,00	NA	NA	NA	NA	NA
		γ_{br13} γ_{brIL2}	2,15	NA	NA	NA	NA	NA
		γ_{br23} γ_{brIL1}	2,15	NA	NA	NA	NA	NA

Note 1: NA = Not applicable.

Appendix 2 Laminates Characteristics and Analysis

1 Application

1.1 General

1.1.1 The scantling check of a laminate is carried out by the calculation of safety factors.

The following parameters are to be taken into account to characterise a laminate:

- two geometric parameters to characterise the individual layers:
  - fibre/resin mix ratio
  - individual layer thickness.
- five in-plane elastic coefficients to characterise the laminate:
  - longitudinal Young modulus
  - transverse Young modulus
  - two Poisson coefficients
  - shear modulus.

1.1.2 Definitions

In the present Appendix, the term ‘laminate’ is used to define the material made from several individual layers, and the term ‘panel’ or ‘laminate panel’ to define a part of the composite propeller.

1.1.3 Panel rule analysis

The purpose of the present Appendix is to define the:

- theoretical main characteristics of a laminate (see Article [2])
- behaviour of a laminate under bending moments, shear forces and in-plane forces (see Article [3])
- panel rule analysis under external loads (see Article [4])

2 Laminate basic characteristics

2.1 General

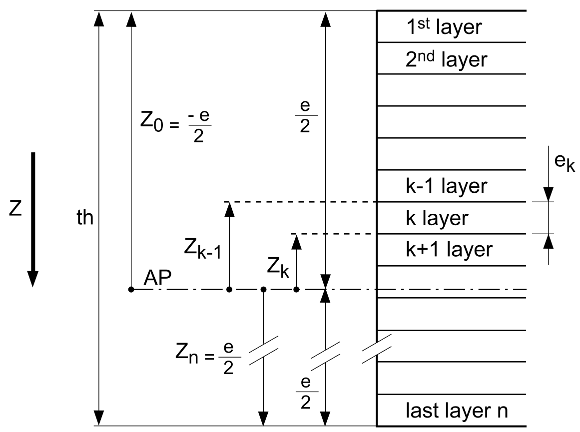
2.1.1 The basic characteristics considered depend on the:

- characteristics of each individual layer, as defined in App 1
- position of each individual layer through the laminate thickness, as shown in [2.1.2]
- orientation of each individual layer in relation to the laminate global axes, as defined in [2.1.3].

2.1.2 Position of individual layers

The position of each individual layer through the laminate thickness is referenced as shown on Fig 1.

Figure 1 : Position of individual layers



AP : Median plane of the laminate, located at mid-thickness of the laminate

th : Laminate thickness, in mm

e_k : Thickness of individual layer k, in mm

Z_k : Distance between AP and interface of layers k and k+1:

$$Z_k = \frac{-e}{2} + \sum_1^k e_i$$

Z_{k-1} : Distance between AP and interface of layers k and k–1:

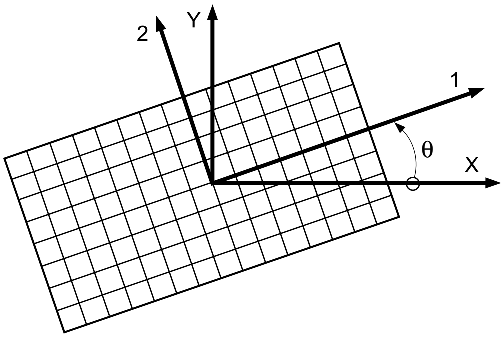
$$Z_{k-1} = \frac{-e}{2} + \sum_1^{k-1} e_i$$

2.1.3 Orientation of individual layers

The orientation between each individual layer local axes and laminate global axes is defined in Fig 2.

Note 1: Angle θ is considered positive from the global axes to the local axes, as shown on Fig 2.

Figure 2 : Orientation of individual layers in relation to the laminate global axis



2.1.4 Conversion of individual layers characteristics

The matrix of rigidity $[R]_k$ and the matrix of flexibility $[S]_k$ of an individual layer k in the laminate global axes are obtained as follows:

$$[R]_k = \begin{bmatrix} R_{XX} & R_{XY} & R_{XZ} \\ R_{YX} & R_{YY} & R_{YZ} \\ R_{ZX} & R_{ZY} & R_{ZZ} \end{bmatrix}_k = T[\bar{R}]_k T'^{-1}$$

$$[S]_k = \begin{bmatrix} S_{XX} & S_{XY} & S_{XZ} \\ S_{YX} & S_{YY} & S_{YZ} \\ S_{ZX} & S_{ZY} & S_{ZZ} \end{bmatrix}_k = T'[\bar{S}]_k T^{-1}$$

where:

$[R]_k$, $[S]_k$: Rigidity and flexibility matrices, respectively, of an individual layer k in its local axes, as defined in App 1

T and T′ : Transfer matrices equal to:

$$T = \begin{bmatrix} (\cos\theta)^2 & (\sin\theta)^2 & -2\cos\theta\sin\theta \\ (\sin\theta)^2 & (\cos\theta)^2 & 2\cos\theta\sin\theta \\ (\cos\theta\sin\theta) & (-\cos\theta\sin\theta) & ((\cos\theta)^2 - (\sin\theta)^2) \end{bmatrix}$$

$$T' = \begin{bmatrix} (\cos\theta)^2 & (\sin\theta)^2 & -\cos\theta\sin\theta \\ (\sin\theta)^2 & (\cos\theta)^2 & \cos\theta\sin\theta \\ (2\cos\theta\sin\theta) & (-2\cos\theta\sin\theta) & ((\cos\theta)^2 - (\sin\theta)^2) \end{bmatrix}$$

where:

T^{-1}, T'^{-1} : Inverse of transfer matrices T and T′, respectively.

2.1.5 Laminate weight

The total weight per square metre of a laminate, in kg/m², is equal to:

$$W = \left(\sum_1^n \frac{P_{fi}}{M_{fi}}\right) 10^{-3} + \sum P_i$$

where:

Pfi : Mass per square metre, in g/m², of dry reinforcement fabric of each individual layer, as defined in App 1
Mfi : Content in mass of fibre for each individual layer, in %, defined in App 1
P_i : Weight of foam and adhesive per square metre, in kg/m², for sandwich laminate.

2.2 Elastic coefficients of laminates

2.2.1 Moduli and poisson ratio

The main tensile moduli E_X and E_Y of a laminate, in N/mm², in its two main directions X and Y, are obtained from the following formulae:

- in X direction:

$$E_X = \frac{1}{A'_{11} \cdot th}$$

- in Y direction:

$$E_Y = \frac{1}{A'_{22} \cdot th}$$

The in-plane shear modulus G_{XY}, in N/mm², of a laminate is obtained from the following formula:

$$G_{XY} = \frac{1}{A'_{33} \cdot th}$$

The main poisson ratio ν_X and ν_Y of a laminate in its two main directions X and Y, are obtained from the following formulae:

- in X direction:

$$\nu_X = \frac{A_{21}}{A_{22}}$$

- in Y direction:

$$\nu_Y = \frac{A_{12}}{A_{11}}$$

where:

A'_{11}, A'_{22}, A'_{33} : Terms of the reverse matrix A defined in [2.3.2]
A_{11}, A_{22}, A_{12}, A_{21}: Terms of the matrix A defined in [2.3.1]
th : Thickness, in mm, of the laminate.

2.2.2 Laminate neutral axis position

The distances V_X and V_Y, in mm, between the global neutral axis of a laminate and the edge of its first individual layer, are defined, in its two main directions X and Y, by the following formulae:

- In X direction:

$$V_X = \frac{\sum E_{Xi} \cdot e_i \cdot Z_i}{\sum E_{Xi} \cdot e_i}$$

- In Y direction:

$$V_Y = \frac{\sum E_{Yi} \cdot e_i \cdot Z_i}{\sum E_{Yi} \cdot e_i}$$

where:

E_{Xi} : Modulus of each individual layer in direction X of the laminate, in N/mm², as defined in [2.2.1]
E_{Yi} : Modulus of each individual layer in direction Y of the laminate, in N/mm², as defined in [2.2.1]
e_i : Thickness of each individual layer, in mm, as defined in [2.2.1]
Z_i : Distance, in mm, between the edge of the laminate and the mid-thickness of each layer, as defined in App 1, [2.2.1].

2.2.3 Laminate bending rigidity

The global bending rigidity, in N·mm²/mm, of a laminate may be expressed, in its two main directions X and Y, from the following formulae:

- in X direction:

$$[EI]_x = \frac{1}{D'_{11}}$$

- in Y direction:

$$[EI]_y = \frac{1}{D'_{22}}$$

where:

D'_{11}, D'_{22} : Terms of the reverse matrix D defined in [2.3.1]

2.3 Matrix notation

2.3.1 Global rigidity matrix

The global rigidity matrix is defined as follows:

$$\begin{bmatrix} A & B \\ B & D \end{bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix}$$

with:

A_{ij} : Tensile rigidity (matrix [3x3])

$$A_{ij} = \sum_1^n (R_{ij})_K \cdot e_k$$

B_{ij} : Tensile and bending coupling effect (matrix [3x3])

$$B_{ij} = \frac{1}{2} \cdot \sum_1^n (R_{ij})_K \cdot (Z_k^2 - Z_{k-1}^2)$$

D_{ij} : Bending rigidity (matrix [3x3])

$$D_{ij} = \frac{1}{3} \cdot \sum_1^n (R_{ij})_K \cdot (Z_k^3 - Z_{k-1}^3)$$

2.3.2 Reverse global rigidity matrix

The reverse global rigidity matrix is defined as follows:

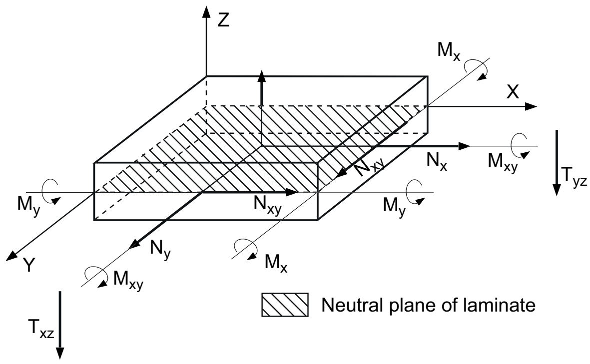
$$\begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} = \begin{bmatrix} A' & B' \\ B' & D' \end{bmatrix}$$

3 Laminate behaviour under external loads

3.1 General

3.1.1 The present Article defines the behaviour of a laminate and the distribution in each individual layer of strains and stresses under bending moments M_i, shear forces T_i and in-plane forces N_i, as shown on Fig 3.

Figure 3 : Application of forces and moments



3.1.2 Bending moments M_i and shear forces T_i

Bending moments M_x and M_y result from external loads applied perpendicular to the laminate plane, as defined in Sec 6, [3.2.2].

Bending moment M_{xy} results from a torsional moment according to Fig 3.

Shear forces T_{xz} and T_{yz} result from external loads applied perpendicular to the laminate plane, as defined in Sec 6.

3.1.3 In-plane forces N_x

In-plane tensile force, N_x results from centrifugal force as defined in Sec 6.

3.2 Laminate behaviour under bending moments M_i and in-plane force N_i

3.2.1 Deformation of laminate median plane

Strains and curved deformations of the laminate median plane are obtained from the following formula:

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \cdot \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \cdot 10^{-3} \\ M_y \cdot 10^{-3} \\ M_{xy} \cdot 10^{-3} \end{bmatrix}$$

where:

ε^0_x : Tensile or compression strain of the laminate median plane in X direction

ε^0_y : Tensile or compression strain of the laminate median plane in Y direction

γ^0_{xy} : Shear strain of the laminate median plane in XY plane

K_x : Curved deformation of the laminate median plane around Y axis

K_y : Curved deformation of the laminate median plane around X axis

K_{xy} : Curved deformation of the laminate median plane around Z axis

$[ABD]^{-1}$: Reverse global rigidity matrix, as defined in [2.3].

3.2.2 Strains of individual layers in the laminate global axes

The in-plane strains ε_x , ε_y and γ_{xy} of each individual layer, calculated at its mid-thickness in the laminate global axes, are given by the following formula:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \cdot \frac{Z_k + Z_{k-1}}{2}$$

Note 1: As a general rule, for core materials, the values of ε_x and ε_y are to be calculated at each interface between the core and the laminate skins.

3.2.3 Strains and stresses of individual layers in their own local axes

The in-plane strains ε_1, ε_2 and γ_{12} of each individual layer, calculated at its mid-thickness in its own local axes, are given by the following formula:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}_k = T'^{-1} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k$$

where:

T' : Transfer matrix defined in [2.1.4] for each individual layer.

The local stresses σ_1, σ_2 and τ_{12} in an individual layer expressed in its own local axes, at mid-thickness, are defined by the following formula:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}_k = [\bar{R}] \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}_k$$

where:

[R] : Rigidity matrix defined in App 1 for each individual layer.

Note 1: For core material of sandwich laminates, the local stresses are expressed, in its own local axes, at top and bottom of the core thickness.

3.3 Laminate behaviour under out plane shear forces T_i

3.3.1 Interlaminar shear stress in laminate global axes

The interlaminar shear stresses τ_{xz} and τ_{yz} between two layers k and k–1, in the global X and Y directions of the laminate induced by shear loads, are determined by the following formula:

$$\begin{bmatrix} \tau_{yz} \\ \tau_{xz} \end{bmatrix}_k = \begin{bmatrix} H_{44} & H_{45} \\ H_{54} & H_{55} \end{bmatrix}_k \cdot \begin{bmatrix} T_{yz} \\ T_{xz} \end{bmatrix}$$

where:

T_{xz}, T_{yz} : Shear loads normal to the median plane of the laminate as shown on Fig 3

$[H_{44}]_k$, $[H_{45}]_k$, $[H_{54}]_k$, $[H_{55}]_k$: Shear constants of layer k, equal to:

$$H_{44} = [C_{yz}]_{k,5} - [R_{21}\ R_{22}\ R_{23}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{12} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{12} \\ Z_{k-1} \cdot B'_{22} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{22} \\ Z_{k-1} \cdot B'_{32} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{32} \end{bmatrix}$$

$$H_{45} = [C_{yz}]_{k,6} - [R_{21}\ R_{22}\ R_{23}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{13} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{13} \\ Z_{k-1} \cdot B'_{23} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{23} \\ Z_{k-1} \cdot B'_{33} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{33} \end{bmatrix}$$

$$H_{54} = [C_{xz}]_{k,6} - [R_{11}\ R_{12}\ R_{13}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{13} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{13} \\ Z_{k-1} \cdot B'_{23} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{23} \\ Z_{k-1} \cdot B'_{33} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{33} \end{bmatrix}$$

$$H_{55} = [C_{xz}]_{k,4} - [R_{11}\ R_{12}\ R_{13}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{11} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{11} \\ Z_{k-1} \cdot B'_{21} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{21} \\ Z_{k-1} \cdot B'_{31} + \dfrac{Z_{k-1}^2}{2} \cdot D'_{31} \end{bmatrix}$$

with:

$[R_{ij}]_k$: Terms of the matrix of rigidity of the layer k defined in App 1

B'_{ij}, D'_{ij} : Terms of the reverse global matrix defined in [2.3.2]

$[C_{yz}]_{k,5}$, $[C_{yz}]_{k,6}$: Fifth and sixth terms of the matrix $[C_{yz}]_k$ defined hereafter

$[C_{xz}]_{k,4}$, $[C_{xz}]_{k,6}$: Fourth and sixth terms of the matrix $[C_{xz}]_k$ defined hereafter

$[C_{yz}]_k$, $[C_{xz}]_k$: Shear distribution coefficients for individual layer k (matrix 1x6) equal to:

$$[C_{yz}]_k = [C_{yz}]_{k-1} + \left\{[R_2]_k - [R_2]_{k-1}\right\} \cdot [M]_k$$

$$[C_{xz}]_k = [C_{xz}]_{k-1} + \left\{[R_1]_k - [R_1]_{k-1}\right\} \cdot [M]_k$$

with:

$[C_{xz}]_{k-1}$, $[C_{yz}]_{k-1}$: Shear distribution coefficients (matrix [1x6]) for layer k–1

$[R_1]_k$, $[R_1]_{k-1}$: First line of matrix of rigidity [R] (defined in [2.1.3]) for layers k and k–1

$[R_2]_k$, $[R_2]_{k-1}$: Second line of matrix of rigidity [R] (defined in [2.1.3]) for layers k and k–1

Note 1: For the first layer (k = 1), the following coefficients are to be taken equal to zero.

$[C_{yz}]_{k-1} = [C_{xz}]_{k-1} = [R_2]_{k-1} = [R_1]_{k-1} = 0$

with:

$[M]_k$: Matrix 3x6 defined as follow:

$$[M]_k = [\,[M_{AB}]_k\,[M_{BD}]_k\,]$$

where:

$[M_{AB}]_k$: Matrix 3x3 equal to:

$$[M_{AB}]_k = \left[Z_{k-1} \cdot A' + \frac{Z_{k-1}^2}{2} \cdot B'\right]$$

$[M_{BD}]_k$: Matrix 3x3 equal to:

$$[M_{BD}]_k = \left[Z_{k-1} \cdot B' + \frac{Z_{k-1}^2}{2} \cdot D'\right]$$

A′, B′, D′ : Terms of the reverse global rigidity matrix [ABD] as defined in [2.3]

3.3.2 Interlaminar shear stress in individual layer local axis

The interlaminar shear stresses between two layers k and k–1, in the local orthotropic axes of the individual layers, are obtained from the following formula:

$$\begin{bmatrix} \tau_{23} \\ \tau_{13} \end{bmatrix}_k = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} \tau_{yz} \\ \tau_{xz} \end{bmatrix}_k$$

τ_{23} and τ_{13} are also named, respectively, τ_{IL1} and τ_{IL2}.

4 Rule analysis of laminate under external loads

4.1 General

4.1.1 The panel analysis is carried out by a “ply by ply” analysis of the laminate.The stresses in each layer of the laminate are calculated as defined in Article [3], taking into account the bending moments M_i and the shear forces T_i induced by the external loads defined in Sec 6, [3.2.2].

The main scantling criteria to be checked are:

a) Maximum stress in each layer:

The main stresses in each layer of the panel laminate are to be in compliance with the following criteria:

$\sigma \leq \sigma_{br} / SF$

$\tau \leq \tau_{br} / SF$

where:

σ, τ : Actual stresses in each layer as defined in [3.2.3] and [3.3.2] respectively

σ_{br}, τ_{br} : Theoretical breaking stresses of layers as defined in NR546

SF : Safety factor as defined in Sec 6.

b) Combined stress in each layer:

The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 6.

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